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Vol. VIII MARCH, 1921 No. 3

BOSTON SOCIETY OF CIVIL ENGINEERS

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PROCEEDINGS

PAPERS IN THIS NUMBER.

"The New Methods of Proportioning Concrete, in Theory and Practice." By Roderick B. Young.

"Several Years' Experiments on the Disposal of Worcester Sewage." By Roy S. Lanphear.

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Contributors are hereby notified that proof will not be submitted to them for examination unless requested before the 10th of the month preceding the month of publication.

MINUTES OF MEETINGS.

BOSTON, February 16, 1921. — A regular meeting of the Boston Society of Civil Engineers was held this evening at Chipman Hall, Tremont Temple, and was called to order at 7.50 o'clock by the President, Frank A. Barbour.

There were 108 members and visitors present.

The records of the last meeting were read and approved.

The Secretary reported for the Board of Government, the election to membership of the following candidates in the grades named:

Members — Henry T. Burrage, William H. Cronin, John J. Murphy, Frank J. Nowell, Percy A. Shaw.

Juniors — Eugene Mirabelli, Merritt P. Smith, George N. Watson.

Mr. Winslow moved the adoption of the following vote, which was passed at the last meeting, and it was carried unanimously:

Voted: That the entire income of the Permanent Fund for the current year be appropriated and placed at the disposal of the Board of Government for use in payment of the current expenses of the Society.

The President announced the death of Louis B. Vaughan, which occurred on July 23, 1920, and by vote he was authorized to appoint a committee to prepare a memoir.

The speaker of the evening, Mr. William N. Connor, was then introduced. Mr. Connor presented a most interesting paper, entitled "Construction Costs," which was illustrated with lantern slides.

The paper was discussed by Messrs. Leonard C. Wason, J. Arthur Garrod, Luzerne S. Cowles and others.

After passing a vote of thanks to Mr. Connor, on motion of Mr. Cowles the Society adjourned at 9.10 o'clock.

S. E. TINKHAM, *Secretary.*

BOSTON, February 2, 1921. — A meeting of the Sanitary Section was held in the Society Rooms, and was opened at 7.50 P.M. by Chairman Edward Wright. The minutes of the previous meeting were read and approved.

The Chairman announced the appointment of the special committee on Plumbing Regulations, authorized at the last session, as follows: Messrs. R. S. Weston, H. A. Varney and E. H. Rogers.

It was moved, seconded and carried, that the Chairman appoint a committee of three to report nominations of officers for the ensuing year at the next meeting.

The Chairman suggested that there be a dinner prior to the annual meeting, March 2. There being no expression of objection, Mr. Wright stated that arrangements to that end would be made and the place of the dinner announced in the notice for the meeting.

Mr. R. S. Lanphear was then introduced and held the interest of his audience of 32 with his address upon "Several Years' Experiments in the Treatment of Worcester Sewage." His description of the conduct and results of the experimental work at Worcester which lead to the adoption of the Imhoff Tank-Trickling Filter method in preference to the Activated Sludge Process, on account of the unusual character of the Worcester sewage, was followed by general discussion.

Mr. Fales moved a rising vote of thanks to the speaker, and the meeting was adjourned at 10 P.M.

Respectfully submitted,

A. L. SHAW, *Acting Clerk.*

FEBRUARY 9, 1921. — A meeting of the Designers Section was called to order at 6.08 P.M., with Chairman Ralph W. Horne presiding.

There were 40 present.

The minutes of the previous meeting were read and approved. A motion was carried that the Chairman appoint a committee of three to report, at the annual meeting, nominations of officers for the ensuing year. Howard Thomas, E. S. Parker and F. A. Marston were named for this committee.

Mr. John R. Nichols was then introduced and outlined the principles and practices with respect to "Flat Slabs — Design and Building Codes," illustrating variations in the dependence which the framers of codes in various cities have seen fit to place upon the peculiar characteristics of this type of construction. A general discussion followed, in the course of which Mr. F. A. Marston described an unusual special problem in flat slab design which he had recently had to meet.

After extending a vote of thanks to Mr. Nichols the meeting adjourned at 8.05 P.M.

Respectfully submitted,

A. L. SHAW, *Clerk.*

APPLICATIONS FOR MEMBERSHIP.

[March 15, 1921.]

THE By-Laws provide that the Board of Government shall consider applications for membership with reference to the eligibility of each candidate for admission and shall determine the proper grade of membership to which he is entitled.

The Board must depend largely upon the members of the Society for the information which will enable it to arrive at a just conclusion. Every member is therefore urged to communicate promptly any facts in relation to the personal character or professional reputation and experience of the candidates which will assist the Board in its consideration. Communications relating to applicants are considered by the Board as strictly confidential.

The fact that applicants give the names of certain members as reference does not necessarily mean that such members endorse the candidate.

The Board of Government will not consider applications until the expiration of twenty (20) days from the date given.

ALLEN, JOHN STETSON, Walpole, Mass. (Age 53, b. Walpole, Mass.) After leaving high school did office work for two or three years, then learned carpenter's trade and later, in partnership with his father, conducted a contracting business, and gradually worked into various forms of general contracting and building. At present is president and treasurer of the M. W. Allen Construction Co., Walpole, Mass. Refers to C. M. Allen, J. M. Cashman, G. A. Sampson and R. S. Weston.

CONGER, ALGER ADAMS, Worcester, Mass. (Age 45, b. Gouverneur, N. Y.) Graduate of Cornell University 1897, with degree of C.E. From 1897–99 worked with U. S. Board of Engineers on Deep Waterways on ship canal surveys, plans and estimates; 1899–1900 with the Isthmian Canal Commission on surveys and estimates for Panama Canal; 1900–1 with New York State Barge Canal; 1901–3 with Michigan Lake Superior Power Co., asst. engineer in charge of power house and dock construction; 1903–6 with New York State Barge Canal in charge of plans and specifications for contracts canalized river locks and fixed dams; 1906–11 with J. G. White & Co., assistant hydraulic engineer, water-power development; 1911 to date, hydraulic engineer, Power Construction Co. and New England Power Co., on development, maintenance and operation of power plants and storage. Refers to C. M. Allen, H. K. Barrows, A. C. Eaton and G. G. Shedd.

DeMerritt, Robert Elwyn, Fort Sherman, Canal Zone, Panama. (Age 27, b. Orange, Mass.) September, 1912, to February, 1914, student at Mass. Inst. of Tech.; summer of 1914, rodman and transitman for C. E. Carter, Reading, Mass.; 1914–15, student at Tech.; September, 1915, to January, 1916, draftsman and assistant engineer, Bay State Railway; February, 1916, to June, 1917, student at Tech.; summer of 1916, transitman, chief of party and inspector, Sewer Division, Woonsocket, R. I.; September to November, 1917, inspector and assistant engineer, Sewer Division, Constructing Quartermaster's office, Camp Devens, Mass.; November, 1917, to May, 1918, 2d Lieut., Coast Artillery Corps, U. S. Army; May, 1918, to date, 1st Lieut., Coast Artillery Corps, U. S. Army. Now at Fort Sherman, Canal Zone. Refers to C. E. Carter, H. F. Davis, G. L. Hosmer and J. W. Howard.

Steward, Douglas Patten, Medford, Mass. (Age 19, b. Lynn, Mass.) Three years as rodman with the B. & M. R. R., and at present is a sophomore at Tufts Engineering School. Refers to R. Abbott, S. P. Coffin, J. J. Rourke, A. T. Sprague, Jr., H. M. Steward and W. A. Woods.

LIST OF MEMBERS.

ADDITIONS.

Cronin, Walter L. . . . . .51 Claybourne St., Dorchester, Mass.
Holbrook, Parker .6 Hancock St., Winchester, Mass.
Leary, Charles A. . . . . .6 Beacon St., Boston 9, Mass.
Martin, Albert A. .505 Centre St., Milton 86, Mass.
Mirabelli, Eugene . . . . .20 Pleasant St., Dorchester 25, Mass.
Murphy, John J. . . . . .4 Deering Road, Boston 26, Mass.
Nowell, Frank J. . . . . .20 Danville St., W. Roxbury, Mass.
Smith, Merritt P. .25 Linwood St., Arlington, Mass.
White, David J. . . . . .62 Condo St., East Boston, Mass.
Wright, Frank V. . . . . .14 Forrester St., Salem, Mass.

CHANGES OF ADDRESS.

Bissell, H. . . . . .21 Esther St., Pasadena, Calif.
Brown, C. Leonard . . . . .810 Taylor St., N. W., Washington, D. C.
Brown, T. Morris . . . . .52 S. Arlington Ave., East Orange, N. J.
Burleigh, Willard G.,
Care The Man Message Corp., 620 Fifth Ave., New York, N. Y.
DePuy, Clarence S. . . . . .Halifax Hotel, Halifax, N. S.
Fair, Gordon M.,
Care League of Red Cross, 9 Cour de St. Pierre, Geneva, Switzerland.
Hodges, A. W. . . . . .489 So. Main St., Randolph, Mass.
Stearns, Ralph H. . . . . .Room 3112, 120 Broadway, New York, N. Y.
Tucker, Francis C. . . . . .1938 Home Ave., Rogers Park, Chicago, Ill.
Umstead, Charles H. . . . . .331 C St., N. W., Washington, D. C
Wood, Leonard P. . . . . .Asst. Designing Engr., Board of Water Supply,
2200 Municipal Bldg., New York, N. Y.

DEATHS.

Andrews, David H.	February 24, 1921.
Bildt, August F.	February 14, 1921.
Scorgie, James C.	February 16, 1921.
Vaughan, Louis B.	July 23, 1921.

LIBRARY NOTES.

Recent Additions to the Library.

U. S. Government Reports.

Chief of Weather Bureau Report. 1919–1920.

Chief of Engineers of U. S. Annual Reports. 1920. 3 vols.

Primary Traverse in Iowa, Kansas, Missouri, Nebraska and Oklahoma. 1916–18.

Triangulation and Primary Traverse in Kentucky and Tennessee. 1916–18.

Triangulation in Maine and New Hampshire. 1916–18.

Utilization of Black Walnut. Bulletin No. 909.

Water Supply Paper No. 467.

State Reports.

New Hampshire. Annual Report, Public Service Commission. 1919.

New Hampshire. Report of Commission on Water Conservation and Water Power. 1919–1920. Geo. B. Leighton, in coöperation with U. S. Geol. Survey.

Municipal Reports.

Lynn, Mass. Annual Report, Commissioner of Water Supply. 1919.

Erie, Pa. Annual Report, Commissioners of Water Works, 1918 and 1919.

Miscellaneous.

Abertkaw Tests on Concrete in Sea Water.

Construction of Roads and Pavements. Agg.

Phosphate in Canada. H. S. Spence, M.E.

Report on Road Materials along the St. Lawrence River. R. H. Picher.

Report on Proportioning Concrete. R. B. Young.

Report on Concrete Aggregate Investigations. R. B. Young and W. D. Walcott.

Ships and Shipmasters of Old Providence.

The Quebec Bridge. By St. Lawrence Bridge Co.

LIBRARY COMMITTEE.

Vol. VIII · MARCH, 1921 No. 3

BOSTON SOCIETY OF CIVIL ENGINEERS
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PAPERS AND DISCUSSIONS

This Society is not responsible for any statement made or opinion expressed in its publications

THE NEW METHODS OF PROPORTIONING CONCRETE IN THEORY AND PRACTICE.

By Roderick B. Young.*

(Presented January 26, 1921.)

In the last few years extensive and systematic experimental studies have been made upon concrete and its constituent materials. These have resulted in important discoveries and additions to our knowledge of the properties of concrete, especially as to what governs a proper combination of its constituents, — cement, aggregate and water. Some progress has already been made in applying these new discoveries in a practical way, and it is the purpose of the speaker to describe the steps taken along this line and the results so far obtained by the concern with which he is connected.

The first of the discoveries referred to is the water-cement-ratio-strength relation developed by Prof. Duff A. Abrams of the Lewis Institute, Chicago. Abrams claims that for mixtures of concrete materials with aggregates from a given source, the strength depends on only one factor, the ratio of water to cement, called for convenience the "water-cement ratio"; that this relation holds so long as the concrete is workable and that the character of the aggregate makes little difference so long as it is clean and not structurally deficient. This relationship was first illustrated by the data from which Fig. 1 is derived, which covers a series of tests of 6 x 12 in. cylinders of sand and gravel concrete using aggregates of different grading, made into mixes of different proportions and of various consistencies. All results of tests on concrete mixtures having consistencies dry beyond the point of workability have purposely been omitted from the curve.

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* Senior Assistant Laboratory Engineer, Hydro-Electric Power Commission of Ontario, Toronto, Ontario.

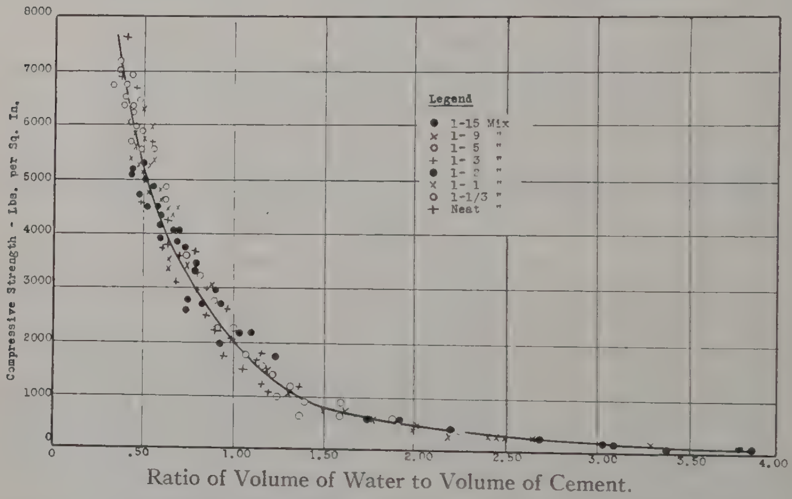


FIG. 1. — RELATION BETWEEN WATER-CEMENT RATIO AND COMPRESSIVE STRENGTH OF CONCRETE (ABRAMS).

One would judge from the foregoing that the relationship was independent of grading, consistency and proportions so long as these fall within practicable limits. This is not so. With cement and aggregate from the same source the relationship varies with all three and in a very definite manner. Instead of the relationship being a simple one, it is the reverse, and concerning which but little is as yet known. A full discussion of the water-cement-ratio-strength relationship is beyond the scope of this paper and would be highly technical and of little interest except to specialists. However, the relationship is of such great practical value in proportioning concrete that we will discuss briefly some of its peculiarities.

For the sake of simplicity the speaker has prepared a series of hypothetical curves showing the characteristics of the variations where the effect of each of the three variables, grading, consistency and proportions, is studied. These curves are based on actual data but are not to be taken as general, as other conditions than here assumed might alter both their form and sequence.

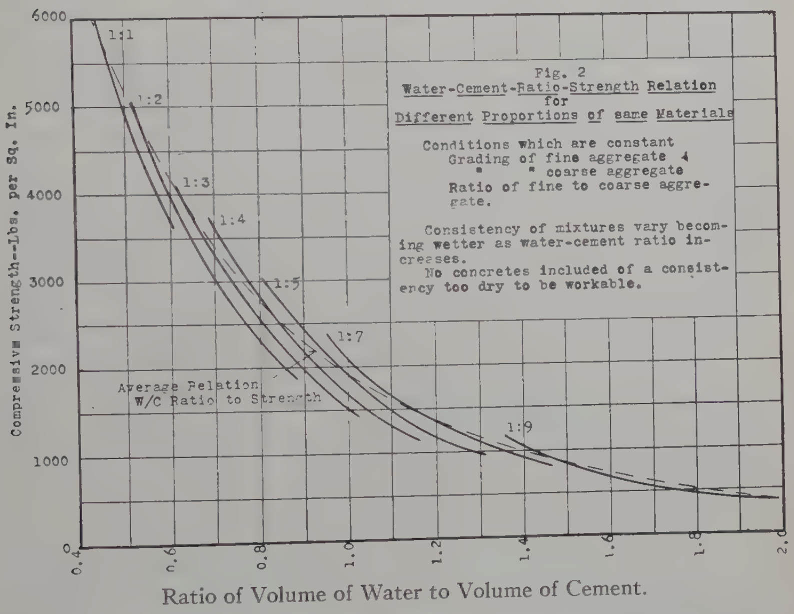
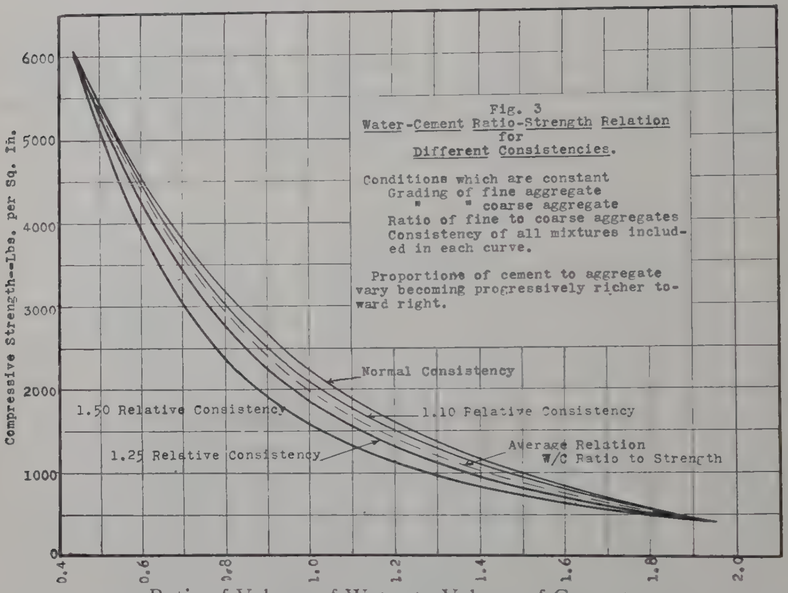


FIG. 2. — VARIATIONS IN WATER-CEMENT-RATIO-STRENGTH RELATION FOR DIFFERENT PROPORTIONS OF SAME MATERIALS. (HYPOTHETICAL CURVES.)

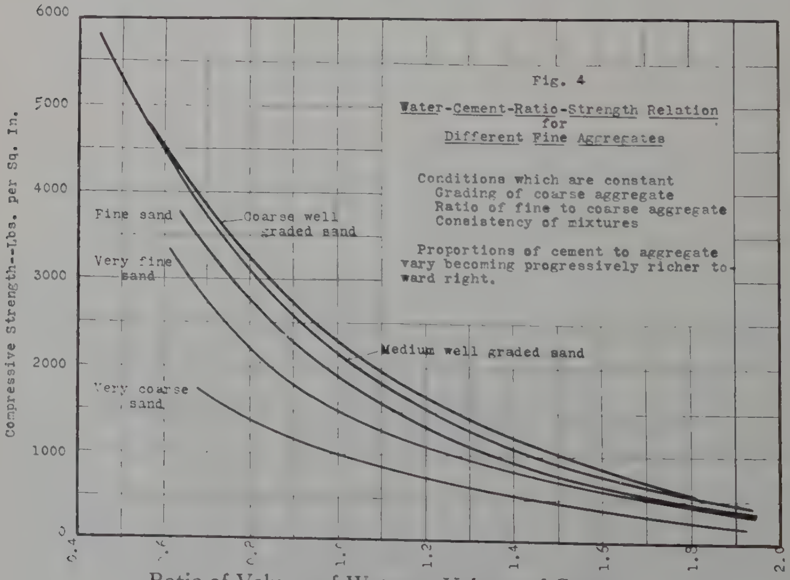
Fig. 2 shows the type of curve which results where aggregates of the same grading are mixed in different proportions. The curve of each proportion is made up necessarily of concrete mixtures of different consistencies but contains no concretes so dry as to be unworkable. These curves are seldom coincident, and then only for short distances, but they not infrequently intersect.

Fig. 3 shows the type of curve which results when the points of equal consistency or workability in Fig. 2 are joined. These new curves represent concretes of equal consistency which have



Ratio of Volume of Water to Volume of Cement.

FIG. 3. — VARIATION IN WATER-CEMENT-RATIO-STRENGTH RELATION FOR DIFFERENT CONSISTENCIES. (HYPOTHETICAL CURVES.)



Ratio of Volume of Water to Volume of Cement.

FIG. 4. — VARIATION IN WATER-CEMENT-RATIO-STRENGTH RELATION FOR DIFFERENT FINE AGGREGATES. (HYPOTHETICAL CURVES.)

been made from aggregates the same both in character and gradation. The proportions of cement to aggregate vary for each curve from very lean mixtures at the extreme right to very rich mixtures at the extreme left.

Fig. 4 shows the type of curve which results where fine aggregates of different grading are made up with different proportions of cement and aggregate to form mixtures of the same consistency. In general, well-graded sands of similar minerological characteristics though of different mechanical analyses will not vary greatly in strength for equal water-cement ratios. As sands increase in fineness or coarseness there is a falling off in strength, the relative loss in strength being different under different circumstances. It must be borne in mind in considering these curves that mixtures of equal water-cement ratio are not of the same proportions of cement and aggregate and that therefore the relative economy of different sands cannot be obtained from a consideration of these curves alone.

Fig. 5 shows the type of curve which results where concretes of the same consistency and proportions are used but having the ratio of fine to coarse aggregate varying. The mixtures at the left of each curve contain an excess of sand as ordinarily considered, the oversanding of the mix decreasing toward the right. This particular chart would illustrate an extreme condition where the fine aggregate was a very fine sand; with well-graded concrete sands the curves tend to flatten out and become coincident.

If these last four charts and others like them covering a variety of gradings, consistency and proportions, were combined, the result would be an area in which the major portion of each curve would lie and which could be approximated by a single curve. This is what has happened in Fig. 1, where the multiplicity of tests included has obscured the fundamental variations to which the water-cement ratio is subject.

How, then, can this relationship which is so complex be of any practical value? It is because of the fact that, within the range of grading, consistency and proportions ordinarily met with on any one piece of work, the variation of strength for any one water-cement ratio is not ordinarily sufficiently great to result in serious error, and while the relationship is variable it is possible to use it in practical work to proportion mixtures which can be predicted to give compressive strengths of the value sought. Therefore, despite the fact that the water-cement-ratio-strength relation is unreliable in many particulars, it offers a means of determining the strength of concrete mixtures which is a distinct advance over anything we have had in the past.

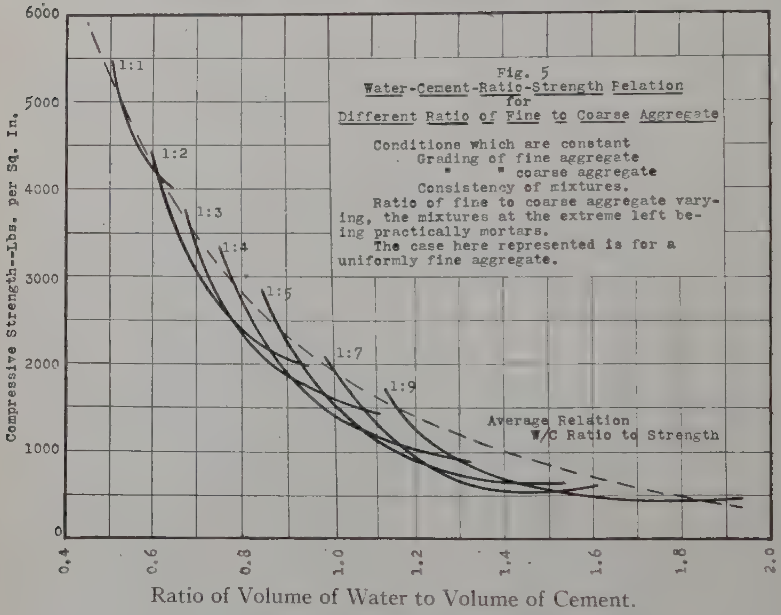


FIG. 5. — VARIATION IN WATER-CEMENT-RATIO-STRENGTH RELATION FOR DIFFERENT RATIO OF FINE TO COARSE AGGREGATE. (HYPOTHETICAL CURVE.)

Professor Abrams has also developed a method of evaluating quantitatively the grading of a sand or other aggregate by means of what he has named its "fineness modulus." His experiments have shown that the fineness modulus of a material is related to its concrete-making properties. This fineness modulus is obtained from its sieve analysis and is found by summing the percentages of material remaining on each of the sieves used in the analysis and dividing this sum by 100. Professor Abrams has standardized on a particular set of sieves, the basic sieve of which is the No. 100 having a sieve opening of 0.0058 in. In each succeeding sieve of this series the opening is double the width of the preceding one. One of the disadvantages of the "fineness modulus" method of determining the effective grading of an aggregate lies in its dependence on a particular series and type of sieve.

Professor Abrams claims that this fineness modulus enables one to interpret properly the sieve analysis of an aggregate and that all aggregates of the same fineness modulus require the same quantity of water to produce a mix of the same plasticity and give concrete of the same strength, provided of course that the aggregate is not too coarse for the quantity of cement used. This is not in conflict with the water-cement ratio theory just described, for the fineness modulus simply reflects the changes in water-cement ratio necessary to produce a given plastic condition.

Working independently on the same general problems, Mr. L. N. Edwards developed experimentally a method of proportioning mortars and concretes by the surface area of their aggregates. Mr. Edwards concluded from his tests that in mortars of the same consistency and made of the same cement and sand the strength obtained is proportional to the relation existing between the cement content and the surface area of the aggregate. He further found that with a given cement and with sands from the same origin the quantity of water required to produce mortars of equal consistency is a function of the water required to reduce the cement to a "normal" paste and the surface area of the particles to be wetted.

In other words, Mr. Edwards claims a relation between strength and surface area and between mobility and surface area, and his tests support his theories so far as mortar mixtures are concerned. Tests since made by the Hydro-Electric Power Commission, under the direction of the speaker, show that these conclusions are under the same conditions equally applicable to concrete mixtures.

Fig. 6 shows the results of a series of tests on mortars by Mr. Edwards which support his claims as to the relation between strength and surface area, and Fig. 7 a similar curve for concrete obtained from tests in the laboratories of the Hydro-Electric Power Commission.

A corollary of Mr. Edwards's proposition is that if mortars or concretes were proportioned with the same ratio of cement to surface area of aggregate and mixed to the same consistency or degree of workability, the resulting strength would be equal. This conclusion was supported by a series of tests

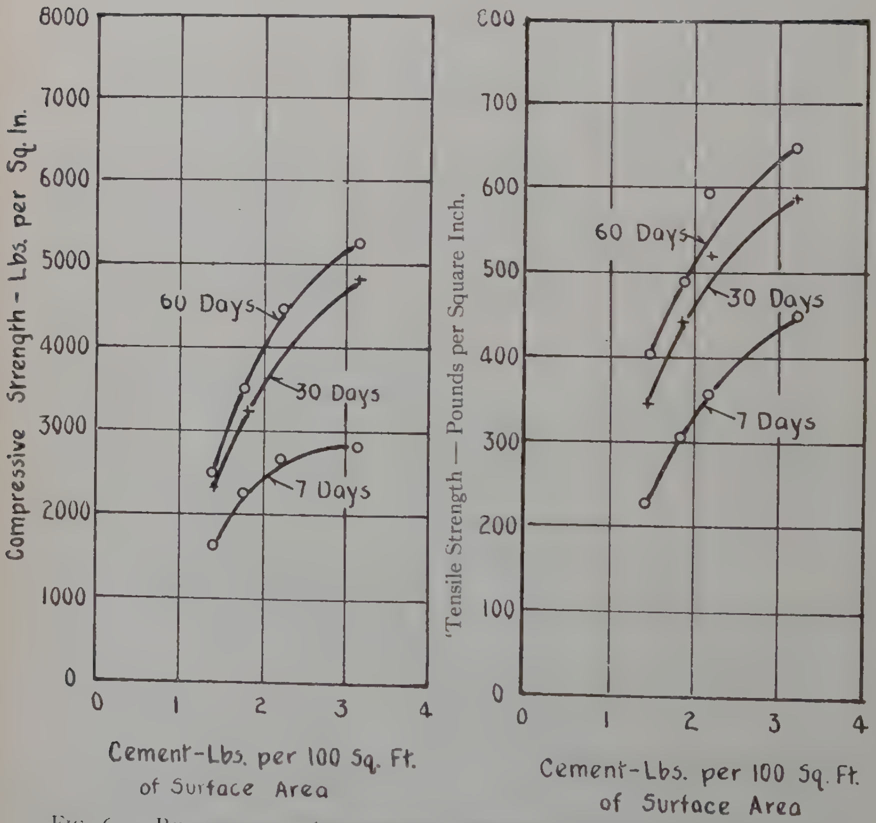


FIG. 6. — RELATION OF STRENGTH OF MORTARS TO VOLUME OF CEMENT IN MIX (EDWARDS, 1918).

(Fig. 8) in which this was found to be so. This, in a general way, has been found to be true of concretes.

Mr. Edwards obtains the surface area of an aggregate by counting and weighing some of each size of grain obtained in its sieve analysis, and from this data determining the average number of particles per unit weight for each size. Then, assuming these to be spherical, and knowing their specific gravity, he calculates the average volume per particle, the surface area per

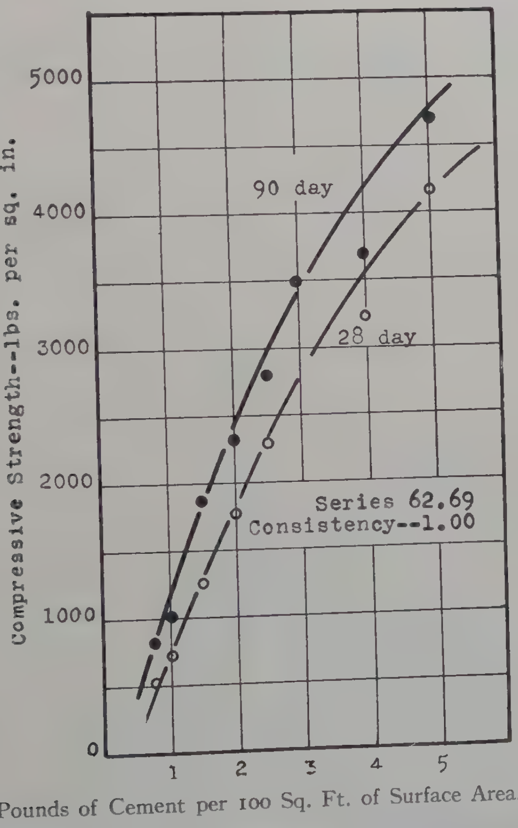


FIG. 7. — RELATION BETWEEN COMPRESSIVE STRENGTH AND VOLUME OF CEMENT IN MIX FOR CONCRETE. (HYDRO-ELECTRIC POWER COMMISSION OF ONTARIO.)

particle, and hence the total surface area per unit weight for each size of separation. This can be done more simply by applying the formula developed by the speaker:

$$A = 236.1 \sqrt[3]{\frac{n}{S^2}}$$

where A equals surface area in square feet per 100 lbs., S equals specific gravity of the sand, and n equals number of grains per gram in any size of separation.

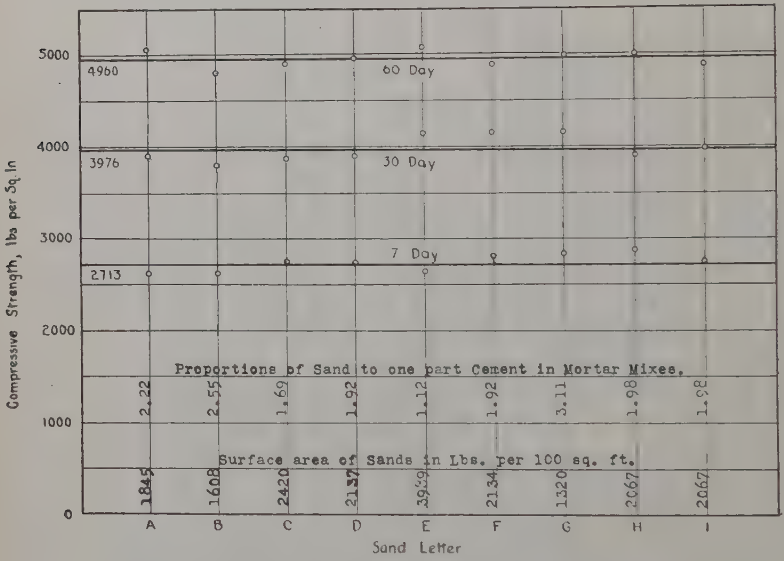


FIG. 8. — COMPRESSIVE STRENGTHS OF 2-IN. MORTAR CYLINDERS PROPORTIONED BY SURFACE AREAS (EDWARDS).

The surface area of any mixed material can be found by multiplying the surface area per unit weight of each size of separation by the weight of that size present in the material, and adding these. The value thus obtained is not the true surface area, for the latter cannot be obtained, as the particles are not true spheres, are variable in shape, and have not smooth surfaces. However, this value undoubtedly bears a constant relation to the true surface area and for all practical purposes is equally as useful.

Mr. Edwards's tests emphasize the relation between strength and surface area but recognize the effect of water by stating that this relationship holds only for concretes of the same consistency. He found it possible to maintain mortars of uniform consistency by proportioning the water in them by a formula involving the surface area of the aggregates used. In other words, to obtain mortar mixtures of equal consistency and strength it was necessary to proportion both the cement and water by surface area.

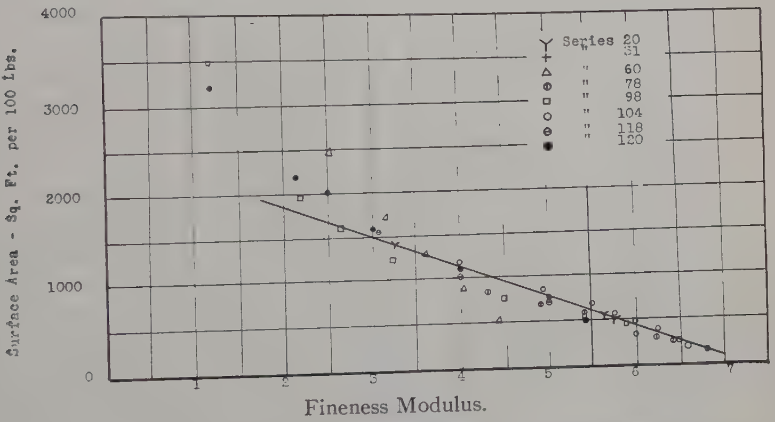


FIG. 9. — RELATION BETWEEN FINENESS MODULUS AND SURFACE AREA OF AGGREGATE. (DERIVED FROM ABRAMS' DATA.)

Mr. Edwards is therefore using surface area as a means of evaluating the grading of an aggregate in much the same way as Professor Abrams uses fineness modulus. Both are used to determine the proper proportions for concrete of a desired strength and having a given degree of workability. Both use a formula involving these to determine the proper amount of water to obtain this degree of workability. It would be reasonable to expect, therefore, that the surface area and fineness modulus would be related in some way. It may be said that this is both the fact and not the fact. There is no mathematical relationship between fineness modulus and surface area, although both their formulæ involve a function of the diameter of the particles of aggregate. If, however, the surface area and fineness modulus of a number of graded concrete aggregates are calculated and plotted it will be found that the relation between the two can be approximated by a straight line. Fig. 9, which is derived from the published results of Professor Abrams' experiments, illustrates this. The aggregates included were sands and mixed sands and gravels of widely different gradings.

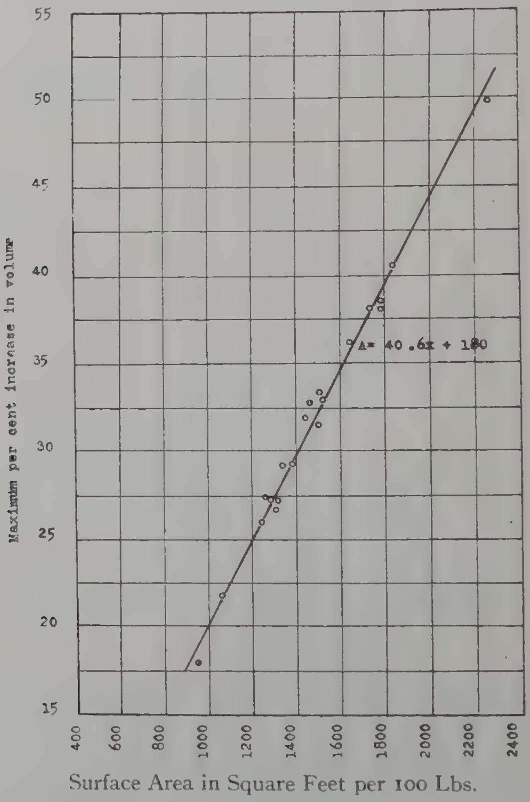


Fig. 10. — Relation between Surface Area and Maximum Bulking for Graded Sands.

It is therefore not correct to say that surface area varies as the fineness modulus, but that it varies similarly to the fineness modulus; and this holds true only with graded aggregates. It is true, as has been stated, that for any one value of fineness modulus there can be an infinite number of values of surface area, or vice versa, but it is equally true that for the average graded aggregate the range of values of fineness modulus for any one value of surface area falls within narrow limits.

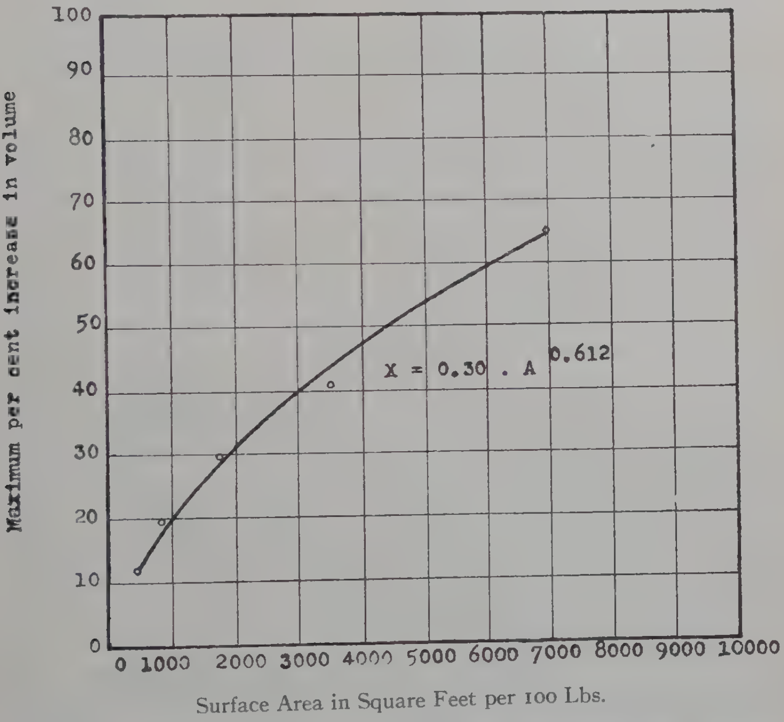


FIG. 11. — RELATION BETWEEN SURFACE AREA AND MAXIMUM BULKING FOR SANDS OF ONE SIZE.

Surface area and fineness modulus are but two different ways of evaluating the same property of an aggregate. Both depend on the grading of the aggregate. Fineness modulus depends also on the particular series and type of sieve used in determining the mechanical analysis of the aggregate, while surface area is entirely independent of the sieves used in its determination. Fineness modulus is therefore the empirical method: surface area, the scientific.

Other properties have been found to be related to the surface area of an aggregate. Consider the effect of moisture on the volume of fine aggregates. As is familiar to all, sand ordinarily occupies more space moist than when dry. It "bulks" due to the moisture contained. That these changes in volume were related to the surface area of the aggregates involved was not known until recently. Figs. 10 and 11 show the relations obtained for graded materials and for materials in which all the particles were approximately of one size. The form of these curves is typical, but the equations expressing the relationships are not general and only hold for the particular methods of test used in this investigation.

Both the relation between water-cement ratio and strength and between surface area, strength and consistency, have been referred to as theories. It is hardly correct to call either "theories" if the word "theory" be used in its strictly scientific sense. The relation between water-cement ratio and strength is influenced by consistency, gradation and proportions in a manner as yet only partially understood. Surface area, likewise, is subject to very definite limitations of which as yet equally little is known. A great deal of investigation remains to be done before either are thoroughly understood.

The proper theory of mixture has yet to be developed. If the speaker may be allowed to predict, he would prophesy that future work will show that this theory will include reference to voids either directly or indirectly, that it will include a function dependent on some property of the aggregated particle such as surface area which can be obtained by a direct test on the aggregates instead of from a mechanical analysis, and that it will involve water-cement ratio only as a secondary function and not as a primary function, as it is now considered.

Methods of proportioning based on the foregoing studies have been developed by Professor Abrams, Mr. Edwards and the speaker. They have much in common. Each is a method of designing concrete mixtures to give specified compressive strengths after certain periods of time. Each has distinct limitations. None offers a panacea for the ills of concrete; the fundamentals of good concrete practice must still be observed. All offer an improvement over the methods of proportioning now in common use.

The method of Professor Abrams is based on his water-cement ratio strength relation and his fineness modulus method of evaluating aggregates. The method is based on the assumption that provided the concretes are plastic and the aggregate is not too coarse for the quantity of cement used, a given compressive strength is always equivalent to the same water-cement ratio. No other limitations are placed on the grading of the aggregate or on the consistency or proportions of the mix.

The method requires a knowledge of the compressive strength of the concrete being proportioned, the class of work for which it is intended, and the consistency of the concrete, mechanical analyses and character of the materials which are to be used in its manufacture.

Knowing the compressive strength, the water-cement ratio equivalent to it is obtained from Fig. 1. Reference is next had to a table of maximum permissible values of fineness modulus for different sizes of aggregate and different proportions, Table I.

TABLE I.

Maximum Permissible Values of Fineness Modulus of Aggregates.

For *mixes* other than those given in the table, use the values for the next leaner mix.

For *maximum sizes* of aggregate other than those given in the table, use the values for the next smaller size.

Fine aggregate includes all material finer than No. 4 sieve; *coarse aggregate* includes all material coarser than the No. 4 sieve. *Mortar* is a mixture of cement, water and fine aggregate.

This table is based on the requirements for *sand-and-pebble* or *gravel* aggregate composed of approximately spherical particles, in ordinary uses of concrete in reinforced concrete structures. For other materials and in other classes of work, the maximum permissible values of fineness modulus for an aggregate of a given size is subject to the following corrections:

(1) If *crushed stone* or *slag* is used as coarse aggregate, *reduce* values in table by 0.25. For crushed material consisting of unusually flat or elongated particles, *reduce* values by 0.40.

(2) For *pebbles* consisting of *flat particles, reduce* values by 0.25.

(3) If *stone screenings* are used as fine aggregate, *reduce* values by 0.25.

(4) For the top course in *concrete roads, reduce* the values by 0.25. If finishing is done by *mechanical means*, this reduction need not be made.

(5) In work of *massive proportions*, such that the smallest dimension is larger than 10 times the maximum size of the coarse aggregate, *additions may be made* to the values in the table as follows: for ¾-in. aggregate, 0.10; for 1½-in., 0.20; for 3-in., 0.30; for 6-in., 0.40.

Sand with fineness modulus lower than 1.50 is undesirable as a fine aggregate in ordinary concrete mixes. Natural sands of such fineness are seldom found.

Sand or screenings used for fine aggregate in concrete must not have a higher fineness modulus than that permitted for mortars of the same mix. Mortar mixes are covered by the table and by (3) above.

Crushed stone mixed with both finer sand and coarser pebbles requires no reduction in fineness modulus provided the quantity of crushed stone is less than 30% of the total volume of the aggregate.

Mix Cem-Agg.	Size of Aggregate													
	0-28	0-14	0-8	0-4	0-3*	0-⅜	0-½*	0-¾	0-1"*	0-1½	0-2.1*	0-3"	0-4½*	0-6"
1-12..	1.20	1.80	2.40	2.95	3.35	3.80	4.20	4.60	5.00	5.35	5.75	6.20	6.60	7.00
1-9...	1.30	1.85	2.45	3.05	3.45	3.85	4.25	4.65	5.00	5.40	5.80	6.25	6.65	7.05
1-7...	1.40	1.95	2.55	3.20	3.55	3.95	4.35	4.75	5.15	5.55	5.95	6.40	6.80	7.20
1-6...	1.50	2.05	2.65	3.30	3.65	4.05	4.45	4.85	5.25	5.65	6.05	6.50	6.90	7.30
1-5...	1.60	2.15	2.75	3.45	3.80	4.20	4.60	5.00	5.40	5.80	6.20	6.60	7.00	7.45
1-4...	1.70	2.30	2.90	3.60	4.00	4.40	4.80	5.20	5.60	6.00	6.40	6.85	7.25	7.65
1-3...	1.85	2.50	3.10	3.90	4.30	4.70	5.10	5.50	5.90	6.30	6.70	7.15	7.55	8.00
1-2...	2.00	2.70	3.40	4.20	4.60	5.05	5.45	5.90	6.30	6.70	7.10	7.55	7.95	8.40
1-1...	2.25	3.00	3.80	4.75	5.25	5.60	6.05	6.50	6.90	7.35	7.75	8.20	8.65	9.10

* Considered as "half-size" sieves; not used in computing fineness modulus.

At this point it is necessary either to assume the mix or the proportions in which the fine and coarse aggregate will be combined. The latter procedure is the simpler. If this is done, the fineness modulus of the combined fine and coarse aggregate can be calculated and, from the table referred to, the leanest permissible mix obtained. A formula is then used to determine the proper quantity of water at the required consistency for this mix and materials of the assumed fineness modulus. If this quantity of water does not give the proper water-cement ratio, the mix or the proportions of fine and coarse aggregate or both must be adjusted until the desired water-cement ratio results.

Professor Abrams has simplified this procedure by developing the nomographic chart, Fig. 12, which includes the four variables, fineness modulus, mix, consistency and strength. This eliminates the calculation of water content and water-cement ratio of the mix and permits the immediate determination of the proper proportions for any consistency and fineness modulus.

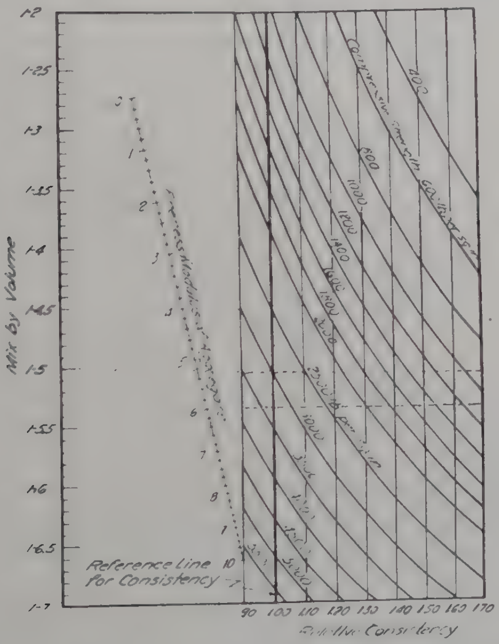


FIG. 12. — DIAGRAM FOR THE DESIGN OF CONCRETE MIXTURES (ABRAMS).

Professor Abrams defines the plastic conditions of concrete by a system of relative consistency. Normal or a relative consistency of 1.00 is of such plasticity that a 6 x 12 in. cylinder of concrete will slump $\frac{1}{2}$ to 1 in. after removal of the metal form by a steady upward pull immediately after molding the specimen. A relative consistency of 1.10 is a concrete mixture having 10 per cent. more water than the same mixture at normal consistency, and is of course increasingly plastic. A relative consistency of 1.10 represents about the driest concrete which can be used in concrete road work, a relative consistency of 1.25 about the wettest concrete which should be used in reinforced concrete building construction.

Mr. Edwards's method is based entirely on surface area. To apply it, it is necessary to know the surface area of the materials to be used and the relation between surface area and cement for concrete of the compressive strength desired. Mr. Edwards does not recognize water-cement ratio or propose an equivalent of Abrams's system of relative consistencies.

The surface area of an aggregate is obtained from its mechanical analysis by the method already outlined. Grain counts of the different materials are not necessary since the data of Edwards's is offered by him as applying to all ordinary materials. Charts and tables are used to simplify this work.

At the present time the relation between surface area and cement for the materials under consideration must be found experimentally for each case. Further investigation may show this relationship so nearly constant that, with a few modifications, one set of values may be found to fit all materials.

In applying the method, the surface area per unit of weight or volume is found for the aggregates, both fine and coarse, from their mechanical analysis and a table or chart of surface areas. A decision must then be made as to the proper combination of the fine and coarse aggregates for the work in hand. This can be had by a study of their mechanical analysis curves, or can simply be set arbitrarily by experience. The cement requirement for a unit volume of mixed aggregate or for an entire batch of concrete can then be obtained by multiplying the surface area of each material in the unit volume or batch by the cement per unit of surface area required for the quality of concrete sought.

In this method no definite provision is made for proportioning mixtures of different consistencies or warning given that the relations established hold only for one consistency. Mr. Edwards in his tests on mortars gaged his mixtures to one degree of plasticity and thus provided a condition fundamental to the success of his method.

A comparison of the two methods is interesting. Edwards does not recognize water-cement ratio, but to obtain concretes of equal strength he proportioned both cement and water by surface area so that their relationship is constant, and mixtures of equal water-cement ratio result. Surface area is in effect the same as fineness modulus and is used for the same purpose in much the same way. Thus fundamentally the two methods are similar.

The method of Abrams has been very fully developed and is offered as applicable to any materials and for concrete mixtures of all workable consistencies. The method of Edwards is equally applicable to all materials and consistencies, but lacks the data essential for its immediate application without special tests for each new set of aggregates encountered. There is little doubt, were studies carried out to obtain this essential information, the surface area method would do anything that the fineness modulus method will do, and do it equally well.

If the speaker were to criticize the fineness modulus method, it would be because it attempts to apply to all materials and conditions without modification. The discussion of the vagaries of the water-cement-ratio-strength relation earlier in this paper shows how unsafe it would be to apply any method based on the assumption that this relation is constant to any and all conditions of practice without checking the results experimentally.

The method of proportioning developed by the Hydro-Electric Power Commission of Ontario was brought about by their adoption of the principle of specifying concrete according to quality instead of by arbitrary proportions. This necessitated the study of a means of obtaining concrete of the desired quality under a variety of conditions. This work was undertaken by the laboratories of the Commission, under the direction of the speaker.

A study was made of both the fineness modulus and surface area methods of proportioning. Neither was considered entirely satisfactory, and after considerable experimental work a method was developed which in many particulars is a compromise between the two older methods.

No attempt has been made by the Commission to develop a method which could be applied anywhere without experimental study of the materials with which it is to be used. The method is not general in this respect but is general in the sense that it can be applied to any materials after their concrete-making properties are once determined.

An analysis of the problem showed two fundamental requirements. The concrete must have a strength at least equal to that fixed by the design of the structure of which it forms a part and during construction it must be sufficiently plastic to handle and place properly.

A means of fulfilling the first condition was found in the relation between water-cement ratio and compressive strength. Without accepting the claim that the water-cement ratio of a mixture absolutely decides its strength, reference to the curves of Figs. 2, 3, 4 and 5 shows that under certain conditions the variation in strength for any one water-cement ratio is very much less than under other conditions and that the conditions under which the variations are a minimum are those which can be provided for by proper supervision and inspection.

The most important of these conditions is a minimum variation in consistency. In designing a concrete mixture which will meet a given water-cement ratio requirement it is necessary to have some method of determining the quantity of water which must be used to obtain a desired workability. This can be done by means of surface area, taking advantage of the fact that the water required to obtain mixtures of constant mobility is a function of the surface area of the aggregate used.

The method of proportioning developed consists, in brief, of obtaining experimentally for each class of concrete and for the concrete materials in hand the relation between water-cement ratio and strength and between cement content and surface area for one degree of plasticity known as "normal consistency." If normal consistency is satisfactory for the particular work in hand, the cement content and water-cement ratio corresponding to the quality of concrete specified are taken from the tests, and the mixtures proportioned accordingly. If the normal consistency is not satisfactory, the consistency is varied as necessary by changing both the cement and water proportionately — thus obtaining the proper water-cement ratio — until the desired workability is obtained.

The experimental investigation consists of a series of tests on concretes made of the materials to be used on the work in question, the cement content of which is proportioned on the basis of surface area and the mixtures of which are all of the same consistency. Usually the information is obtained from a set of thirty-five test cylinders made up in seven different proportions according to the best laboratory practice and tested when twenty-eight days old. Such a series can be made at small cost.

Table II is an example of the results obtained from one of these series. This information is plotted as in Fig. 13 (*a*) and (*b*). From these curves is obtained the information required in calculating the proportions. (Table III.)

TABLE II.

Example of Tests Used to Establish Relation between Cement Content, Water-Cement Ratio and Compressive Strength.

Series 62-69 — Niagara Power Development.

Cement — lbs. per 100 sq. ft.	0.75	1.5	2.0	2.5	3.0	4.0	5.0
Water-cement ratio by weight	1.426	0.843	0.654	0.557	0.498	0.423	0.326
Compressive strength, lbs. per sq. in. (28 days)	519	1 393	1 919	2 262	2 890	3 655	3 686
	441	1 374	2 027	1 980	2 714	2 873	4 310
	487	1 070	1 740	2 462	2 749	3 450	4 380
	617	1 201	1 514	2 347	3 010	2 960	4 623
	...	....	1 636	2 403	2 892	....	3 792
Average	516	1 260	1 767	2 291	2 851	3 235	4 158

TABLE III.

Example of Constants Used for Proportioning Mixtures of Normal Consistency for Different Classes of Concrete.

Class.	Minimum Specified Compressive Strength. Lbs. per Sq. In.	Cement — Lbs. per 100 Sq. Ft. Surface Area Normal Consistency.	Range of Water-Cement Ratio by Weight. Min.	Max.
A.	2 500	1.45	0.48	0.53
B.	2 000	2.00	0.56	0.62
C.	1 500	2.50	0.65	0.73
D.	1 000	3.15	0.80	0.92

It will be noticed that water-cement ratio as used by the Commission is the ration of weight of water to weight of cement. As originally proposed, it was the ratio of volume of water to volume of cement. It was found more convenient to have the ratio on a weight basis, and the change was accordingly made, and this practice is now standard with the Commission.

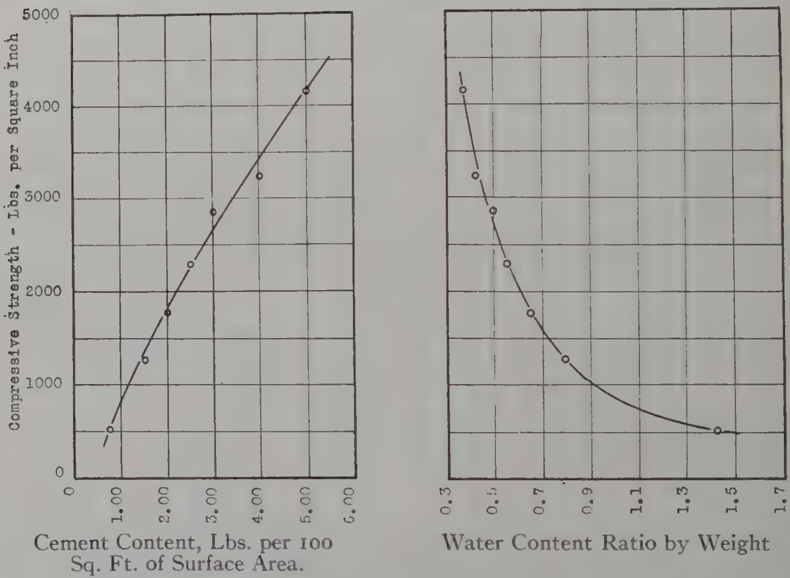


FIG. 13 (*a*). FIG. 13 (*b*).

CURVES, ESTABLISHING RELATION BETWEEN COMPRESSIVE STRENGTH, WATER-CEMENT RATIO AND CEMENT CONTENT AT NORMAL CONSISTENCY.

In Fig. 13 (*a*) is given the relation between cement content and compressive strength at normal consistency, from which can be read the cement requirement at that consistency corresponding to any desired strength. It is customary to allow a margin of several hundred pounds over the minimum requirements of the specification to care for field conditions: the better the inspection and workmanship, the smaller the margin thus necessary.

From Fig. 13 (*b*) can be found the water-cement ratio corresponding to the same strength. The cement content multiplied by this water-cement ratio will give the quantity of water per unit of area which must be used for concrete of the corresponding strength.

All that now remains to be done is to multiply this cement and water content per unit of area by the total surface area of the aggregates to be used in a batch of concrete, putting the results in terms of bags of cement and gallons of water.

The water content of the batch thus determined is the maximum quantity of water which can be present in the mixtures used if concrete of the specified quality is to be obtained. Since in actual work the aggregates already contain an appreciable quantity of water, this must be determined and deducted from the total water before the net amount to be added at the mixer is known. This information is obtained as necessary by determining the moisture contents of the aggregates in the condition used. This test is usually confined to the fine aggregates, as the moisture contained in the average coarse aggregate is of such small amount as to be negligible.

The proper ratio of fine to coarse aggregate is determined from the results of the mechanical analyses of these materials, the effort being made to use as high a percentage of coarse material as possible and still maintain a workable mixture. This varies with the richness of the mix, grading of the sand, consistency, character of the materials, methods of placing and class of work. It must be arrived at, first, by judgment based on past performances, and settled finally by adjustment in the field. In the experimental work which forms the basis of this method of proportioning, a mixture of fine and coarse aggregate is used which will give concretes workable in small masses. This is usually a mixture of 2 parts fine aggregate to 3 parts coarse. The results obtained from such tests have been found to apply satisfactorily to the less sanded field mixtures.

It will be seen that while this method is general in its application, its use in any particular instance requires experimental information on the materials to be employed. In the case of small jobs, the cost of the investigations may be burdensome, but on jobs of a thousand cubic yards or more its cost is but a few cents a yard. The method requires skill in its application, but so too does that of Abrams and Edwards. In their present development none of these methods can safely be used except by men who appreciate their limitations.

This method, while employing the unsatisfactory water-cement ratio strength relation, uses it in such a way as to minimize its shortcomings. The tests are made using a workable consistency with materials graded and combined closely as they will be actually used. In this way the variations in strength for any one value of water-cement ratio are reduced to a minimum.

This method will be applicable to the smaller jobs when more experience has been gained in its use, so that the proper constants for different aggregates, for different gradings and for different cements can be determined with fair accuracy from mortar tests. This phase of the problem is being studied now, and there is every promise that some inexpensive test will be developed for this purpose.

The Commission has used this method on three jobs. It was first applied in the construction of a small dam and power house at High Falls, Ontario, in the summer of 1919. Experience gained there led to the decision to use it on a larger job, and during last summer and fall some 36 000 cu. yds. of concrete were proportioned thereby on a power development under construction on the Nipigon River, north of Lake Superior. Because of the results obtained there it was decided to apply it on still larger work, and in the next twelve months this method will be used to proportion nearly 600 000 cu. yds. of concrete of all classes on three different jobs now under construction by the Commission.

At High Falls approximately 60 sets of test cylinders were made from concrete taken directly from the forms. These were stored in moist sand for two weeks, then packed in damp sawdust and shipped to the Commission's laboratories at Toronto for test. More test specimens were taken on this job than its size warranted because the method was new and under close observation and because the daily yardages poured were small. Table IV contains the results of the tests on these specimens.

The materials used at High Falls were unscreened gravel graded up to one inch and crushed rock screened free from dust. The quantities in Table IV are stated in terms of these materials, which accounts for the odd proportions used.

The results obtained during September, October and November were very satisfactory. The ultimate strengths obtained

TABLE IV.

REPRESENTATIVE RESULTS OF FIELD TESTS OF CONCRETE, HIGH FALLS POWER DEVELOPMENT, HYDRO-ELECTRIC POWER COMMISSION OF ONTARIO.

Class A.

Minimum Compressive Strength, 2 500 lbs. per sq. in.
Maximum Water-Cement Ratio, 0.57.

Date.	Proportions.	Water-Cement Ratio by Weight.	Compressive Strength at 28 Days. Lbs. per Sq.In.
Sept. 16	1–3.3–3.4	0.45	3 338
Sept. 17	do.	0.43	3 730
Sept. 18	do.	0.43	4 060*
Sept. 19	1–3.0–3.2	0.43	3 965*
Sept. 19	1–3.0–3.4	0.43	3 775*
Sept. 19	1–3.3–3.5	0.47	2 780*
Sept. 20	do.	0.44	2 993*
Sept. 22	do.	0.45	3 450
Oct. 3	do.	. . .	3 475
Nov. 11	1–3.0–3.4	0.52	2 920
Nov. 12	do.	0.52	3 356
Nov. 14	do.	0.52	2 175
Nov. 15	do.	0.52	1 950*
Nov. 20	do.	0.52	3 185
Nov. 29	1–3.0–3.2	0.51	3 445
1920.			
Jan. 29	1–2.7–2.2	0.56	2 019
Jan. 29	1–2.5–3.0	0.52	2 498
Feb. 6	1–2.5–2.0	0.52	1 742
Feb. 10	1–2.6–2.0	0.54	2 190
Feb. 11	1–3.0–2.4	0.57	1 966
Feb. 12	do.	0.57	2 280†
Feb. 17	1–2.6–2.0	0.52	2 470†
Feb. 18	do.	0.52	2.380†
Mar. 26	1–2.6–1.4	0.52	2 380*

Except where noted, results are average of tests on two specimens.

* Test on single specimen.

† Average of tests on three specimens.

Class B.

Minimum Compressive Strength, 2 000 lbs. per sq. in.
Maximum Water-Cement Ratio, 0.64.

Date.	Proportions.	Water-Cement Ratio by Weight.	Compressive Strength at 28 Days. Lbs. per Sq. In.
Oct. 8	1-3.6-3.8	0.64	2 100
Oct. 10	do.	0.64	1 785†
Oct. 11	1-3.6-4.7	0.64	1 815*
Oct. 16	1-3.6-3.8	0.64	1 963
Oct. 17	do.	0.64	2 447
Oct. 18	do.	0.64	2 785
Nov. 27	do.	0.59	3 360
Dec. 2	do.	0.59	1 856
Dec. 3	do.	0.59	1 825
Dec. 4	do.	0.59	2 034
Dec. 11	do.	0.59	1 943
Dec. 13	do.	0.59	1 868
Dec. 21	do.	0.59	1 820
Dec. 23	do.	0.59	2 100
1920.			
Jan. 1	do.	0.64	1 594*
Jan. 5	do.	0.63	958
Jan. 9	1-3.3-3.5	0.64	1 068
Jan. 9	1-3.6-3.8	0.62	613
Jan. 14	1-3.6-2.9	0.62	1 132
Feb. 5	1-3.4-3.6	0.62	1 530
Apr. 3	1-3.9-2.8	0.59	1 750
Apr. 3	1-3.6	0.59	1 902†
Apr. 4	1-3.0-1.6	0.59	2 867†

Except where noted, results are average of tests on two specimens.

* Test on single specimen.
† Average of tests on three specimens.

Class C.

Minimum Compressive Strength, 1 500 lbs. per sq. in.
Maximum Water-Cement Ratio, 0.74.

Date.	Proportions.	Water-Cement Ratio by Weight.	Compressive Strength. Lbs. per Sq. In.
1920.			
Feb. 20........	1–4.5–2.4	0.74	1 068†
Feb. 23........	do.	0.74	1 778†
Feb. 23........	1–4.3–3.2	0.76	1 335*
Feb. 23........	1–4.5–3.6	0.74	2 025*
Feb. 25........	1–4.5–2.4	0.74	1 175
Feb. 25........	1–4.0–2.1	0.74	1 237
Feb. 27........	1–2.0–3.9	0.74	1 726
Mar. 1.........	1–3.9–3.0	0.74	1 713†
Mar. 4.........	do.	0.74	1 671†
Mar. 8.........	1–3.6–1.9	0.74	1 431†
Mar. 10........	1–3.9–2.0	0.74	1 732*
Mar. 11........	do.	0.74	1 493†
Mar. 24........	do.	0.74	1 437
Apr. 22........	do.	0.74	2 190
Apr. 22........	1–3.9–2.8	0.74	1 505‡

Except where noted, results are average of tests on two specimens.

* Test on single specimen.
† Average of tests on three specimens.
‡ Average of tests on four specimens.

during these months are considerably in excess of the minimum required, but this was due mainly to the use of a drier consistency than the proportions were designed for. It was considered inadvisable to take advantage of this and use leaner proportions, because of our inexperience with the method.

After cold weather set in, a change was noticed in the test results, which began to drop below the expected values. The reason was sought, and the trouble was found to be in the samples. It was difficult to maintain their storage at proper temperature in the temporary buildings used for this purpose. It was impossible to protect them from the cold in their long journey to Toronto. The result was that setting was retarded an indeterminate amount with consequent decrease in strength.

Experience at High Falls lead to the recommendation that a field laboratory be installed at Nipigon, and that a specialist in concrete be used on this work for the inspection of materials and the supervision of the processes of concreting.

A small laboratory was installed and was equipped with an inexpensive 100-ton hydraulic-type testing machine, sieves for the analysis of sand and stone, and miscellaneous apparatus for determining their weight per cubic foot, moisture content, cleanliness and freedom from organic impurities. A small building was erected to house the apparatus and for the storage of the concrete test specimens.

An experienced concrete engineer from the Toronto Laboratories was assigned to the staff of the resident engineer. His duties covered supervision of the laboratory and inspection of both materials and operations.

Inspection on this job was very thorough. The materials were not only tested but a watch was kept on the sand and gravel pits, washing plant, crusher and stock piles. The inspection of concreting included all details in connection with proportioning, mixing and placing. An effort was made to see that materials were accurately measured, that the batches were properly mixed and that the chuting plant was arranged so as not to interfere with the quality of the concrete delivered. Inspection was also maintained on the placing of concrete, spadding, laitance and removal of forms.

The same system of taking and curing test specimens was followed here as at High Falls. Eighty sets of 8 x 16 in. cylinders, representing 36 000 cu. yds., were made. One cylinder was broken at seven days, the other two at twenty-eight days. The seven-day tests were only possible because of the laboratory facilities provided at hand. They were chiefly valuable as indicative of quality and were of little use in determining the probable strength at the later age.

Conditions at Nipigon made it more difficult to maintain the quality of the concrete there than at High Falls. Due to the cement situation last summer it was necessary to obtain supplies from six different mills. Sand was obtained from two different sources, a gravel pit and a sand pit. The pit sand was fine and micaceous and required more cement than a better graded sand. The gravel screenings were dirty and required washing. When available it was mixed with the pit sand to improve the grading of the latter. The variations in the materials were great, were difficult to anticipate and compensate for, and added materially to the problem of proportioning the mixtures accurately.

The tests made to date at Nipigon have been tabulated in Table V. For the first five months the results obtained were better than at High Falls. During the last two months, October and November, they were less satisfactory. The cooler weather may have been in part to blame for this, but only in part, as the samples were protected as far as possible from low temperatures. The work was a rush job, and toward the last the concreting was pushed to the utmost with consequent loss in efficiency, making inspection more difficult. The result was inevitable, — the quality of the concrete suffered.

Concrete is now being placed on the Niagara Power Development of the Commission under the same method. A complete field laboratory is being installed, as at Nipigon; a concrete engineer has been assigned to the supervision of the inspection and testing of the concrete. This will be very thorough and will necessitate a large organization. Five hundred thousand cubic yards of concrete of all classes is to be placed on this job in the next twelve months. Some has already been placed and the results obtained to date have been very satisfactory.

At High Falls about 70 per cent. of the sets averaged better than 200 lbs. per sq. in. under the design strength. At Nipigon, if all the tests are included, 60 per cent. come in this class. If the results of the last two months, which are not a fair indication of what can be done under normal conditions, are included, approximately 80 per cent. are in this category. At Niagara Falls somewhat better results are being obtained.

In general we are well satisfied with this method of proportioning. While one hundred per cent. control has not been obtained, our experience has indicated the paths that lead toward this goal. The method will design concrete mixtures of given strength and consistency, but present practice in measuring materials before mixing allow such variations in the sand and stone content of a batch that any attempt to be precise in determining the proper proportions are rendered abortive thereby.

TABLE V.

Representative Results of Field Tests of Concrete, Nipigon Power Development, Hydro-Electric Power Commission of Ontario.

Class A.

Minimum Compressive Strength, 2 500 lbs. per sq. in.
Maximum Water-Cement Ratio, 0.60.

Date.	Proportions.	Water-Cement Ratio. Weight.	Ultimate Strength at 28 Days. Lbs. per Sq. In.	
			7-Day.	28-Day.
June 5	1–2.5–3.0	0.54	....	2 330†
June 6	1–1.8–3.2	0.55	....	2 660†
June 11	1–1.7–3.2	0.54	....	3 360
June 16	1–1.8–3.2	0.54	2 360	3 415
June 27	1–2.0–4.0	0.57	2 190	3 288
June 30	1–2.0–3.9	0.57	2 740	3 238
July 7	1–2.1–3.4	0.57	2 181	3 050
Aug. 3	1–2.2–3.7	0.56	1 509	2 982
Aug. 5	do.	0.56	2 281	2 902
Aug. 11	1–2.7–4.0	0.60	2 790	2 820
Aug. 14	1–3.0–5.5	0.61	1 990	2 821
Aug. 19	1–2.3–3.7	0.59	1 125	3 505
Aug. 20	do.	0.58	1 535	2 225
Sept. 2	1–2.2–3.8	0.57	1 221*	2 525‡
Sept. 4	do.	0.57	1 194	2 352
Sept. 8	do.	0.59	1 235	2 396
Sept. 9	do.	0.59	1 390	2 625
Sept. 13	do.	0.58	1 203*	2 468‡
Sept. 15	do.	0.58	1 280	2 465
Sept. 16	do.	0.58	1 115	2 085
Sept. 21	1–2.2–3.9	0.60	634	2 535
Sept. 24	do.	0.60	927*	2 425‡
Sept. 27	do.	0.60	905	1 745
Sept. 30	do.	0.60	1 173*	2 363‡
Oct. 1	do.	0.60	871	1 826
Oct. 2	do.	0.60	630	1 343
Oct. 5	1–1.6–2.9	0.57	951	2 240
Oct. 19	1–1.9–5.4	0.54	1 371*	2 271‡
Oct. 27	do.	0.55	792	1 470
Oct. 31	1–2.2–4.0	0.58	835	1 290
Nov. 2	1–1.9–3.4	0.56	1 275	1 762
Nov. 3	do.	0.56	1 268	2 217
Nov. 7	do.	0.58	916	1 141
Nov. 8	do.	0.60	951	1 232
Nov. 9	do.	0.56	795	1 256
Nov. 15	do.	0.56	986	1 602

Except where noted, 7-day results are single test specimens; 28-day results are average of two test specimens.

* Average of tests on two specimens.
† Average of tests on three specimens.
‡ Average of tests on four specimens.

Class B.

Minimum Compressive Strength, 2 000 lbs. per sq. in.
Maximum Water-Cement Ratio, 0.68.

Date.	Proportions.	Water-Cement Ratio. Weight.	Ultimate Strength at 28 Days. Lbs. per Sq. In.	
			7-Day.	28-Day.
May 24	1–2.5–4.5	0.60	....	2 535†
May 28	do.	0.60	....	2 560†
May 30	1–2.0–3.1	0.55	....	2 460†
June 2	do.	0.55	....	2 430†
June 9	1–2.5–3.7	0.60	....	2 110§
June 11	1–2.3–3.8	0.60	1 314	2 270
June 15	1–2.3–3.3	0.60	1 512	2 937
June 20	do.	0.60	961	2 032
Aug. 17	1–2.6–4.6	0.64	1 395	2 605
Aug. 26	do.	0.68	755	2 180
Aug. 28	do.	0.67	835	1 365
Sept. 18	do.	0.64	1 354	2 060
Sept. 25	1–2.2–3.9	0.64	1 030	1 683
Oct. 3	1–2.6–4.6	0.68	1 025	1 817
Oct. 5	1–2.3–3.8	0.66	1 103	2 220
Oct. 8	do.	0.66	712	2 297
Oct. 9	do.	0.66	631	1 640
Oct. 14	1–2.6–4.6	0.67	494	1 379
Nov. 11	1–2.2–4.0	0.66	710	1 397

Except where noted, 7-day results are single test specimens; 28-day results are average of two test specimens.

† Average of tests on three specimens.

§ Test on single specimen.

Class C.

Minimum Compressive Strength, 1 500 lbs. per sq. in.
Maximum Water-Cement Ratio, 0.81.

Date.	Proportions.	Water-Cement Ratio. Weight.	Ultimate Strength at 28 Days. Lbs. per Sq. In.	
			7-Day.	28-Day.
May 13	1–2.3–4	0.56	....	1 640†
June 4	1–2.5–4.5	0.72	....	1 835†
June 14	1–3.0–5.0	0.72	1 300	2 125
June 29	do.	0.80	1 310	2 090
July 7	1–3.2–4.5	0.80	1 110	2 592
July 17	1–3.0–5.4	0.80	395	1 430
July 20	1–3.3–5.5	0.80	1 680	1 927
July 30	do.	0.75	1 062	1 630
Aug. 7	do.	0.79	1 180	2 335
Aug. 10	1–2.9–5.0	0.77	1 390	2 062
Aug. 12	1–3.3–5.5	0.77	1 260	2 752
Aug. 13	1–2.6–5.5	0.71	1 180	2 125
Aug. 22	1–3.3–5.5	0.80	1 100	2 022
Aug. 24	do.	0.80	398	1 437
Oct. 11	1–2.6–4.6	0.77	807	1 895

Except where noted, 7-day results are single test specimens; 28-day results are average of two test specimens.

† Average of tests on three specimens.

Probably few realize the inaccuracies of our present volumetric methods of measuring aggregates. A 2 per cent. change in moisture content of a sand may cause a 15 per cent. difference in the actual quantity per unit volume. In the average measuring hopper a 1-in. variation in the measurement of the fine aggregate will make a 10 per cent. difference in the volume in a batch.

Our experience has shown that most of the trouble with consistency — the occasional dry and wet batches — are directly traceable to variations in measurement. These variations are in turn the cause of much low-testing concrete because of the tendency for the workman after a dry batch or batches to increase the quantity of water in the mix. The most careful and continuous inspection will not prevent this, and even if the accidental variations of measurement were eliminated, those due to moisture changes are alone sufficient to cause appreciable errors.

Probably the greatest single improvement that can be made in our best concrete practice, which it is assumed does not permit the use of excess water and recognizes the need of proper inspection, is not the use of any new method of proportioning but the use of weight measurement of aggregates — particularly sand — in place of the present system of measuring aggregates by volume. This may seem a radical statement but the experience of the Commission fully justified it.

The idea that concrete is a material that can be made by anybody is one of the most pernicious errors existing among engineers. Our method of proportioning is only one part of our system of insuring good concrete, which begins with preliminary investigations of available aggregates, includes studies of their concrete-making properties, continues during construction in rigid inspection and testing of all materials and of every step through which these materials pass before their final deposition in the finished structure, and ends only when the forms are removed and the concrete is ready for service.

The best inspection can only be had by employing men who are conversant with both the theoretical and practical phases of their work. With concrete becoming of such importance and of such wide application, there is no excuse for employing men of less ability, and the additional cost of their service will be offset by the economies they are able to effect and the quality of the work obtained.

Many will question the economy of going to the refinements here recommended except on the very largest jobs. We question their position. The advantages of uniform concrete are obvious. If concrete of uniform quality can be continuously guaranteed by the maker, the present high factors of safety can be reduced. Either less concrete will then be required or concrete of a lower grade can be used. In addition, economies due to the use of less cement for given results are possible under close control. On any but the smallest jobs the advantages obtained will justify the cost.

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4. Analysis of Concrete Proportioning Theories. Roderick B. Young. *Canadian Engineer*, November 27, 1919.

5. Method of Proportioning Concrete by Surface Area. Used on Actual Work. Roderick B. Young. *Engineering News-Record*, January 1, 1920.

6. Example of the Application of Abrams' Water Ratio to Proportioning Concrete. Stanton Walker. American Concrete Institute, Vol. XVI, 1920.

7. The Volume-Moisture Relation in Sand and a Method of Determining Surface Area Based Thereon. R. B. Young and W. D. Walcott. Amer. Soc. for Test. Materials, Vol. XX, Part II, 1920.

DISCUSSION.

L. N. Edwards.*—I appreciate your courtesy in calling upon me to discuss the paper read by Mr. Young, but on account of the lateness of the hour I shall refrain from entering into a lengthly discussion. I desire, however, to call attention to a few phases of the surface-area method of proportioning mortars and concretes, which appear to me to have been but lightly touched upon.

Speaking generally, seventy-five to eighty-five per cent. of the total volume of a concrete is made up of sand and stone aggregates. The strength, hardness, toughness and other physical properties of these aggregates are, therefore, most vital factors in the production of reliable concrete construction work. The extent to which the physical properties of the parent rock remain unchanged in our sands and gravels depends very largely upon the agencies by which these aggregates have been produced. Naturally enough, the sands and gravels produced by the crushing and abrasive action of the glaciers of the Ice or Glacial Age have undergone less change than have those produced by the weathering, decomposing, and disintegrating agencies of all ages. Very briefly, the basic conditions affecting the reliability of our sands and gravels are:

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* State Highway Commission, Augusta, Me.

1. The physical properties of the parent rock.

2. The conditions attending the disintegration of the rock mass.

The surface-area method of proportioning produces, I believe, a practicable means of discovering the mortar and concrete-making qualities of sands and of gravels by which we may learn the strength, hardness and other desirable qualities procurable from their use, with the most economical proportioning of the cement content.

In general, the strengths of concretes are primarily dependent upon the strengths of their mortar contents. The strength of the stone aggregate becomes a dominating factor when its strength is less than the strength of the mortar surrounding it in the concrete mass. The fact that the fractured surface of a concrete shows the particles of stone aggregate (particles of gravel or of broken stone, as the case may be) broken through does not necessarily indicate that practically the same strength could not have been secured with a less cement content, other conditions being equal.

The increasing use of concrete as a structural material and the fact that this use is distributed throughout the entire area of practically every state in the Union would seem to indicate the importance of the making of a general survey of the concrete materials to be found in any given state and the development of information relating to their concrete-making qualities. I believe you will agree with me that a survey of this kind, undertaken even at a comparatively small expense per annum, would provide in a comparatively small number of years the information necessary for charting the locality of available concrete materials and the tabulation of important information concerning them. Doubtless the information thus made available would ultimately result in an economy in the use of cement. However, the securing of structures fulfilling the requirements of their design is a matter of special importance to us as engineers.

In connection with the bulking effect of moisture in sands there exists an interesting detail which is of no special value in so far as concrete making is concerned. In a series of tests made in 1917,* I found that when the moisture content is sufficient to produce a flooded condition of the sand, the volume becomes the same as the original volume of dry sand. In no case did I find that the water had the effect of producing a decrease of this volume.

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* Proceedings Am. Soc. for Test. Mats., Vol. XXVIII, Part II, page 235.

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SEVERAL YEARS' EXPERIMENTS ON THE DISPOSAL OF WORCESTER SEWAGE.

BY ROY S. LANPHEAR.*

(Presented before the Sanitary Section, February 2, 1921.)

THE chemical precipitation plant for treatment of Worcester sewage was placed in operation March 25, 1890. Experimental treatment of sewage on a large scale commenced in 1900, when settled sewage, chemical precipitation effluent and septic tank effluent were run on to sand filters which had been recently constructed. Two years later, filtration of septic tank effluent was abandoned because finely divided suspended matters penetrated the surface of the filters and required frequent removal of large quantities of dirty sand. Settled sewage from the chemical precipitation basins gave similar results of operation. Chemical precipitation effluent also carried finely divided solids on to the sand filters and the precipitation of lime resulted in the formation of a hard crust of the top sand. The rate of filtration of chemical precipitation effluent decreased more than 50 per cent. in five years, and it was necessary to remove as much as 4 ins. of material in a single cleaning in order to regain the original rate of filtration.

Late in 1904, facilities were provided for delivering crude sewage directly to the sand filters, which method of operation continued until September, 1908. Change was then made to the present method of passing the sewage through one or two settling basins which afford a short detention period of about twenty minutes. This change was made to relieve the overloading of the sand filters with scum close to the distributors. The disposal of suspended solids as sludge by pumping is much cheaper than the removal from the filters, and the short detention period of the sewage removes only the heavier and coarser suspended solids.

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Experimental sewage treatment plant operation commenced in 1905, when septic tank effluent and settled sewage were put on to contact filters; two primary beds and one secondary bed, each about 1 200 sq. ft. in area, were filled with 40 ins. of depth of crushed stone, $\frac{3}{4}$ to $2\frac{1}{2}$ ins. in size. The results of operation were unsatisfactory with each influent; a rate of 500 000 gals. per acre daily gave a putrescible effluent much of the time, and the loss of capacity of the beds in a single year was 12 per cent., 4 per cent. during the first six months and 8 per cent. during the second six months.

In 1906, the depth of the primary beds was increased, the stone removed, and they were used as septic tanks for one year, when one tank was operated as a settling tank for septic tank effluent, all as preliminary treatment for trickling filters of 5 and $7\frac{1}{2}$ ft. in depth. Two years later, preliminary treatment was changed to plain sedimentation of sewage, and in 1911 chemical precipitation effluent was applied to the shallow filter. Much valuable data was obtained, but the principal results may be stated as follows:

1. The deeper filters gave the better effluent.

2. Purification was better with septic tank effluent than with settled sewage because ferrous iron of the sewage was removed to some extent in the septic tank by precipitation as sulphide of iron.

3. The odors accompanying filtration of septic tank effluent were very objectionable.

4. Chemical precipitation effluent was filtered at a rate of 1 000 000 gals. per acre daily, and settled sewage at 700 000 gals. per acre daily with equally good results.

5. The cost of chemical precipitation eliminated the consideration of this process as preliminary treatment.

In 1911, an Imhoff tank and two trickling filters were placed in operation, each filter being 10 ft. deep, one with crushed stone $\frac{3}{4}$ to $2\frac{1}{2}$ ins. and the other $\frac{1}{2}$ to $1\frac{1}{2}$ ins. in size. This plant was operated successfully for two years, the rate of filtration during the second year being 2 million gallons per acre daily. The filter of coarser stone did not yield quite as good an effluent as the other, but caused much less trouble with surface pooling of water. Its effluent was non-putrescible during warm weather, and during the winter about 75 per cent. of the samples tested were non-putrescible.

It was appreciated that chemical precipitation of sewage was inefficient and costly, and in 1916 the superintendent of sewers recommended the change to an Imhoff tank-trickling filter sewage disposal plant. The construction of sand filters was discontinued in 1910, when the supply of sand became depleted. About the time of this recommendation, the State Department of Health started considerable agitation for a new sewage treatment plant of the type recommended.

Early in 1917, in keeping with the policy of the Worcester Sewer Department to test out every method of sewage treatment that gave promise of success, an experimental plant using the activated sludge process was constructed and placed in operation. This plant was operated for thirteen months, at the end of which time the supervising chemist was called to military service. During the operation of the plant, difficulty was experienced in obtaining and holding a sufficient number of qualified assistants. Consequently the report upon the operation of the plant was not ready to submit to the superintendent of sewers until November, 1919. This report indicated that the air requirements of Worcester sewage treated by the activated sludge process were large and that disposal of the sludge presented a serious problem.

On May 9, 1919, six months before this report was available, the state legislature, at the instigation of the State Department of Health, passed an Act requiring the city of Worcester to start work on a new sewage disposal plant before October 1, 1919, and to place the plant in operation by April 1, 1924. With no opportunity for the consideration of possible need of further experimentation, the Superintendent of Sewers again recommended that the Imhoff tank-trickling filter process of sewage treatment be adopted, and the State Department of Health approved the same and the proposed location of the plant. The site of this plant is being cleared and the outfall sewer is being extended to the new plant.

EXPERIMENTAL ACTIVATED SLUDGE PLANT.

Description. — The experimental activated sludge plant consisted of a bar screen, grit chamber, sewage aëration tank, sludge re-aëration tank, sedimentation tank, sludge concentration tank and a shallow tank used for sludge concentration experiments and for measuring excess sludge previous to disposal.

Sewage was taken from the outlet of the main grit chambers in a 6-in. pipe line to the screen chamber, where it passed through the screen with ½-in. openings between the bars. It then passed in a trough, by a swivel gate, where excess quantities of sewage were wasted, to a grit chamber, 72 x 10 x 8 ins. deep, formed by a depressed section of the trough bottom. The sewage flow was measured by a weir and hook-gage and then continued in the trough to the sewage aëration tank, the returned sludge entering this trough close to the tank.

The sewage aëration tank was constructed of wood and had a concrete bottom; it was 26 ft. long, 14 ft. wide and 10 ft. deep, — water depth, — and had a capacity of 25 283 gals. The tank was divided into three channels, giving the sewage a travel of nearly 80 ft. The bottom of the tank was of saw-tooth construction, rows of four filtros plates, Grade "S," being placed 45 ins., center to center, giving a ratio of tank surface to working plate area of 5.2 to 1. Concrete blocks were placed between the rows of plates and had slopes of 1.5 on 1. Compressed air was delivered by a 4-in. header to three 2½-in. pipes, one for each channel. Each set of filtros plates was supplied with air by a 1-in. pipe which entered a chamber under the plates made by using a form when putting in the concrete bottom. Each of these pipes had a valve near the top whereby the quantity of air passing to each set of plates could be regulated, but much care had to be exercised in their use in order to avoid trouble.

This method of installing the filtros plates proved very successful, and it is noted that the general use of metal holders is being abandoned. Filtros plates proved satisfactory for the diffusion of air into the sewage and sludge; brushing of the plates was done once, and apparently did no good. Each 1-in. pipe was fitted with a union so that perforated pipe distributors could be substituted for the filtros plates, but results of operation did not warrant such a change during the second summer. No baffles were used in either aëration tank, but such installation in the sewage aëration tank had been considered.

The effluent from the sewage aëration tank passed in a trough to a point above the center of the sedimentation tank and was measured by a weir and hook-gage. The inlet to the sedimentation tank was a box of increasing area of cross-section which extended down into the tank about 8 ft. This tank was of the Dortmund type, 14 ft. in diameter and 9.6 ft. deep, circular section, with a conical bottom, 9 ft. deep, having a slope of 1.5 on 1.0. The capacity of the upper section was 11 058 gals., and of the conical bottom, 4 017 gals. During operation, the conical bottom was usually kept filled with sludge to aid in returning sludge to the sewage which had sufficient and uniform density. The sludge did not slide down this slope readily, and a squeegee was used daily. The effluent was collected in a circumferential trough and the sludge settling to the bottom of the tank was raised by air lift and delivered in a trough, containing swivel gates, to the sewage or sludge aëration tanks or to either of the sludge tanks.

The sludge, with or without re-aëration, was returned to the sewage in a trough previously mentioned, and was measured as the difference of the combined sewage and sludge and the sewage flows. The sludge re-aëration tank was 12 ft. long, 5 ft. 4 ins. wide and 10 ft. deep, and had a capacity of 4 386 gals. Its construction was similar to that of the sewage aëration tank and the ratio of tank surface to air diffuser area was 4.76 to 1.0.

The equipment for furnishing compressed air included two 10 h.p. single-phase motors, belt-connected to two No. 2 Nash hydroturbine compressors or blowers. The air passed through cheesecloth screens and was washed with water in the compressors. Air used for aëration of sewage and of sludge was measured by Venturi meters connected to graduated manometer tubes, and that for the air lift, by a Westinghouse No. 12 gas meter. A pressure gage, thermometer and a waste valve were suitably installed in connection with a storage tank placed between the compressors and the separate air supply mains. The quantity of air used was regulated by adjusting the valves on each supply main and the waste valve. On this account, together with interruptions of operation and the operation of one or both compressors, the pressure data are inconsistent. The average pressure increased from 5¼ lbs. to about 6½ to 6¾ lbs. in the winter, and during the second summer dropped to from 5½ to 6 lbs., indicating the probability of slight clogging of the filtros plates. The higher pressures of winter may be explained in part by interruptions of operation and by the probable increased friction in the air distribution system due to condensation. The air distribution pipes were protected from the winter temperatures by covering with felt and boxing them in.

Operation. — From 125 000 to 165 000 gals. of sewage were screened daily, the screen raked once an hour, and an average quantity of 11.4 cu. ft. of screenings removed per million gallons of sewage screened. Fine screening is apparently not necessary for successful operation, but might result in the reduction of the quantity of air required. On account of the large oxygen requirement of Worcester sewage, due to the presence of large quantities of trade-wastes, the reduction would be relatively small. According to Mr. Hatton, of Milwaukee, fine screening of sewage in this process of treatment should not be carried too far because the resulting activated sludge is difficult to de-water.

The results of operation of the small grit chamber indicate that the treatment of combined sewage by the activated sludge process requires careful design and operation of the grit chambers.

Careful records were kept of all temperatures of operation, and it may be stated that winter operation of the activated sludge process in New England climate is generally possible. For a period of six weeks, the average maximum temperature of the air was below 32 degrees Fahr., and the average minimum below 10 degrees Fahr.; during the first week, the maximum daily temperature varied from 4 degrees to 18 degrees Fahr., and the minimum from −16 degrees Fahr. to −2 degrees Fahr. The results of operation during this period of six weeks were good.

The quantity of sludge returned to the sewage was regulated according to the results of a thirty-minute settling test of the effluent from the sewage aëration tank, the test being made by reading the volume of settled sludge in a 500 c.c. graduated cylinder. Activated sludge in proper condition settles rapidly in this thirty-minutes settling test and after ten minutes will be only about 50 per cent. greater in volume than at the end of the test, and during the last twenty minutes, it settles as a mass or compacts. Variation of density of the sludge and its effect upon the bulk of solids or flocculent sludge necessary for clarification of the sewage are offset by maintaining a uniform percentage of sludge according to this test. Excessive quantities of sludge without sufficient solids always produced an unsatisfactory effluent having a yellow or brown color, while in what might be termed successful operation the supernatant water above the settled sludge had very little turbidity and was colorless. At times, this supernatant water was as clear as spring water within a few minutes after the collection of the sample. This settling test was an excellent indicator of the character of the sludge and the effect of the quantity returned to the sewage. The percentage of solids in the settled sludge in this test was generally greater in the effluent than in the influent, the maximum differences, about 0.2 per cent., occurring when the greater quantities of air and longer periods of aëration were used.

Comparison of results of this thirty-minutes settling test made at the inlet and outlet ends of the sewage aëration tank showed a variation of not more than 0.2 per cent. of sludge. Apparently, precipitation of iron is rapid or aëration of sludge in this tank results in a better settling sludge, and the precipitated iron and suspended solids from the sewage cause no marked difference in the results of the test.

Foaming occurred in the sludge re-aëration tank during the first ten days of operation, and it was necessary to raise the tank walls 9 ins. and cover the tank with chicken-wire to prevent the foam going over the walls. Foaming occurred at other times, usually with the aëration of activated sludge of poor quality.

The character of the re-aërated sludge could be observed quickly by putting a small quantity into some water contained in a glass cylinder. A thirty-minutes settling test of the re-aërated sludge usually gave a percentage of sludge of from 96 to 98; the specific gravity and per cent. solids of the settled sludge varied from 1.010 to 1.015 and from 1.00 to 3.40, respectively, the heavier sludge occurring in the summer season with the use of the larger quantities of air. The water above the settled sludge always had a yellow color, the intensity varying with the color of the sludge. The odor of the re-aërated sludge was generally characterized as a combination of musty, earthy and wormy.

Analyses of the air after use in the aëration tanks showed that oxygen was removed and carbon dioxide formed, about 2.1 and 4.3 per cent. in the sewage and sludge aëration tank, respectively. A small amount of methane and heavy hydrocarbons was also formed.

The sedimentation period of the aërated sewage and sludge, based on the cylindrical portion of the sedimentation tank, varied from 1.6 to 2.9 hrs., which is much longer than is generally considered necessary. This period can probably be shortened, but provision should be made for the continuous removal of reasonably dense sludge, as experience has demonstrated that the return of large volumes of thin sludge to the sewage aëration tank is undesirable. It will also be necessary to arrange for the removal of unsightly grease balls and scum from the water in the sedimentation tank.

Quality of Final Effluent. — The rates of operation will be considered in the next paragraph. Chemical analyses of sewage and final effluent showed a general lack of reduction of free ammonia, considerable reduction of albuminoid ammonia and oxygen consumed, from 85 to 95 per cent. removal of suspended solids, about 90 per cent. removal of iron, and an entire absence of nitrification of the effluent. Clarification was generally excellent and in the absence of nitrification exerted considerable influence upon the stability of the effluent. The dissolved oxygen content of the effluent usually averaged from 20 to 30 per cent. of saturation, but many times was zero in the afternoon.

In general, effluents having less than 0.2 part of total albuminoid ammonia, about 0.05 part per 100 000 of suspended albuminoid ammonia and less than 3.0 parts per 100 000 of suspended solids were of good appearance, but the stability was variable, being influenced by the actual content of organic matter and suspended solids. The effluent usually contained from 50 000 to 350 000 bacteria per c.c. according to the quality, a maximum reduction of 97.5 per cent. being obtained when the maximum quantities of air and periods of aëration were used.

Results of Sewage Treatment. — From 75 000 to 125 000 gals. of sewage were treated daily, using from 2 to 5 cu. ft. of free air per gallon and periods of aëration of sewage from 3.8 to 6.2 hrs. and of sludge, with the exception of one period of six weeks, from 2.8 to 6.5 hrs. The size and character of the plant confined the operating schedule within certain limits in order to obtain accurate records; changes would have been advisable if the operation had not been interrupted.

1. A total quantity of 1.75 cu. ft. of free air per gallon of sewage, together with 3.8 hrs.' aëration of the sewage and 3.1 hrs.' re-aëration of the sludge, using 31 per cent. returned sludge, did not remove the color of the trade wastes from average sewage.

2. A total quantity of 2.16 cu. ft. of free air per gallon of sewage, together with 5.3 hrs.' aëration of the sewage and 5.3 hrs.' re-aëration of the sludge, using 21 per cent. returned sludge and treating weak sewage, gave an effluent having an average stability of about 90 per cent.

3. A total quantity of 1.99 cu. ft. of free air per gallon of sewage, 4.3 hrs.' aëration of the sewage and no re-aëration of the sludge, using 18 per cent. returned sludge and treating very weak sewage, gave an effluent having an average stability of about 60 per cent., but of good chemical quality.

These three statements practically define the treatment of weak Worcester sewage according to the degree of stability desired. Three or four days' stability of the effluent can be obtained without re-aëration of the sludge, when using at least 2 cu. ft. of free air, from 4 to 5 hrs.' aëration of the sewage and about 20 per cent. returned sludge.

4. A total quantity of from 3.3 to 3.6 cu. ft. of free air per

gallon of sewage, 6.3 to 6.5 hrs.' aëration of the sewage and 5.0 to 6.5 hrs.' re-aëration of the sludge, using about 25 per cent. returned sludge and treating fairly strong sewage, gave an effluent having an average stability of about 90 per cent. This result did not always obtain, and the variation or inconsistency is attributed to the character of the sewage.

5. A total quantity of 4.95 cu. ft. of free air per gallon of sewage, 6.3 hrs.' aëration of the sewage and 5.1 hrs.' re-aëration of the sludge, using 27 per cent. returned sludge and treating hardly average sewage, gave an effluent having perfect stability.

6. The results indicate, but with considerable uncertainty on account of the inability to duplicate, that a total quantity of about 4 cu. ft. of free air per gallon of sewage, 6 hrs.' aëration of the sewage and 6 hrs.' re-aëration of the sludge, using about 25 per cent. returned sludge and treating average to strong sewage, should give a final effluent of good chemical quality and having a stability of from 75 to 90 per cent.

7. Elimination of re-aëration of sludge while treating average to strong sewage was not attempted on account of the poor results of the second summer and the interruption of operation of the plant.

Summary of Sewage Treatment. — Worcester sewage contains much trade wastes of such varying character and quantity that nitrification did not take place with the quantities of air and periods of aëration used in the operation of the experimental activated sludge plant. A stable effluent was obtained by the reduction of the organic content of the sewage. Lack of nitrification and low dissolved oxygen content of the effluent furnished no factor of safety or stability, such as is usually present in effluents from biological processes of treatment; consequently, sewage of greatly varying character was not uniformly well treated. Increased quantities of air and periods of aëration would probably overcome the sensitive character of the activated sludge process in treating Worcester sewage and give uniformly good results with apparently similar conditions of treatment.

Comparison of Effluents. Activated Sludge and Imhoff Tank-Trickling Filter Methods of Sewage Treatment. — It has been stated that the activated sludge effluent was generally clear, colorless and of good chemical quality but lacked stability. Treating stronger sewage and operating at a rate of 2 000 000 gals. per acre filter daily, the Imhoff tank-trickling filter experimental plant gave an effluent which was generally slightly turbid, slightly colored at times, of greater organic content, but contained about 0.5 part per 100 000 of nitrogen as nitrates, and was perfectly stable during the warm weather, and 75 per cent. of the samples were non-putrescible during the winter season.

Activated Sludge. — The satisfactory treatment of sewage is usually considered a prerequisite to investigation of methods of sludge disposal, but the extremely large quantity and unusual character of activated sludge produced presented a problem which was of much interest. Activated sludge is flocculent, settles rapidly and has a brown color, the particular shade of which is very variable and apparently due to changes in the character of the sludge. A very dark brown color and loss of flocculent character indicated insufficient aëration, and a very light brown color and a change from flocculent condition to finely divided solids indicated over-aëration. The odor of good activated sludge was generally characterized as earthy, and when not so good its odor resembled that of decaying angleworms, similar to that of sludge from final settling basins following trickling filters.

Sludge Production. — The quantity of activated sludge produced per million gallons of sewage varied from 12 000 gals. in summer to 25 000 gals. in winter; both quantities are much greater than have been produced by any other process of treatment of Worcester sewage. The sludge contained from 97.1 to 98.7 per cent. moisture, the denser sludge being obtained in the summer. The dried sludge contained from 50 to 70 per cent. of organic matter, from 8.5 to 18 per cent. of iron, from 2 to 9 per cent. of fats, and from 4.0 to 6.5 per cent. of nitrogen. Worcester activated sludge was as dense as that which has been obtained elsewhere, and indicates that it will be difficult to obtain activated sludge, without concentration, having less than 97 per cent. moisture.

Air Drying of Sludge. — The greater part of the sludge was dried upon sand beds; this method of disposal is impractical on account of being unable to dose the beds to a depth greater than 4 or 5 ins. If more than this quantity was applied, the sludge settled rapidly and water remained on top, which had to evaporate before actual drying commenced. The dose had to be of such size that the bulk of the water drained away during application to the bed; cracking of dried sludge commenced after twenty-four hours, and removal was possible twenty-four hours later. The usual dose was from 2.0 to 2.5 gals. per square foot of drying bed area. Concentration of sludge improved results very slightly.

Concentration of Sludge. — The first step in disposing of activated sludge on a large scale would be concentration, in order to decrease the volume to be handled. Concentration experiments were made in two tanks, one of which was 14 ft. in diameter, 6 ft. deep and held 2 000 gals.; the other was 3 ft. in diameter, 18½ ft. deep and held 650 gals. Heavier sludge could be drawn from the bottom of the deep tank if extremely long periods of concentration were used, but in no instance was sludge obtained containing less than 95 per cent. moisture. Concentration of sludge for from fifteen to twenty-four hours decreased the volume of sludge about 50 per cent. and its water content from 98 to 96 per cent., the best results being obtained when the sludge was in a flocculent condition. Character of sludge effects the quantity to be handled; that is, poor results of operation as regards sewage treatment may mean increased cost of sludge disposal.

Pressing of Sludge. — A section of a press of the Bushnell type, formerly used for chemical precipitation sludge, was demonstrated to be unsuitable for pressing activated sludge, unless about 2 500 lbs. of lime in the form of milk of lime were added to 100 000 gals. of sludge and pressing made for about two hours at 60 lbs. per square inch pressure. Without the use of lime, various results of pressing were obtained, depending somewhat upon the character of the sludge; but in all cases radial streaks of soft sludge were formed which rendered the press cake unfit for disposal. Our present installation of sludge presses is unsatisfactory for handling activated sludge without preliminary treatment. The results indicated that the successful press should de-water the sludge to about 70 per cent. moisture during the first twenty to thirty minutes of operation, and the addition of lime should not be necessary.

Sludge as Fertilizer Material. — The nitrogen content of activated sludge is greater than that of any other sewage sludge at Worcester. Fertilizer analyses of activated sludge, Imhoff tank and final settling basin sludges are given as follows, the results being percentages and given in the above order.

Substance.	I.	II.	III.
Total nitrogen	4.06	2.61	2.42
Available nitrogen	1.39	1.25	1.71
Total phosphoric acid	2.26	1.66	3.43
Citrate insoluble acid	0.50	0.46	1.16
Citrate soluble acid	1.76	1.20	2.27
Potash*			

* Not determined, varies from 0.0 to 0.05 per cent.

The available nitrogen in the Imhoff tank sludge is but little less than that in the activated sludge, while the final settling basin sludge contained considerably more than did activated sludge. The final settling basin sludge also contained much more total and citrate soluble phosphoric acid than did activated sludge. The actual nitrogen content of activated sludge as compared with combined Imhoff tank and final settling basin sludge, based on unit quantity of sewage treated, is approximately 2½ times as great. If revenue was desired along these lines, facilities would have to be provided for handling six times as much unconcentrated and three times as much concentrated activated sludge as of the combined sludges, and about one and one-half times as much dry solids.

Summary. — The operation of the experimental activated sludge plant for a period of thirteen months demonstrated that this process of treatment of Worcester sewage will produce an effluent of excellent appearance and good chemical quality. The quantity of air required was much greater than that which has been considered possible to use in other cities. This increased air requirement is due in great part to the necessity of reducing the organic content of the effluent to a relatively small quantity in the absence of any nitrogen as nitrates, in order to obtain a stable effluent. The problem of disposal of large volumes of sludge each day was only partially solved, but it was demonstrated that our present sludge press installation was not suitable for handling activated sludge.

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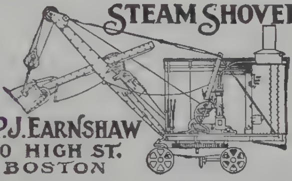

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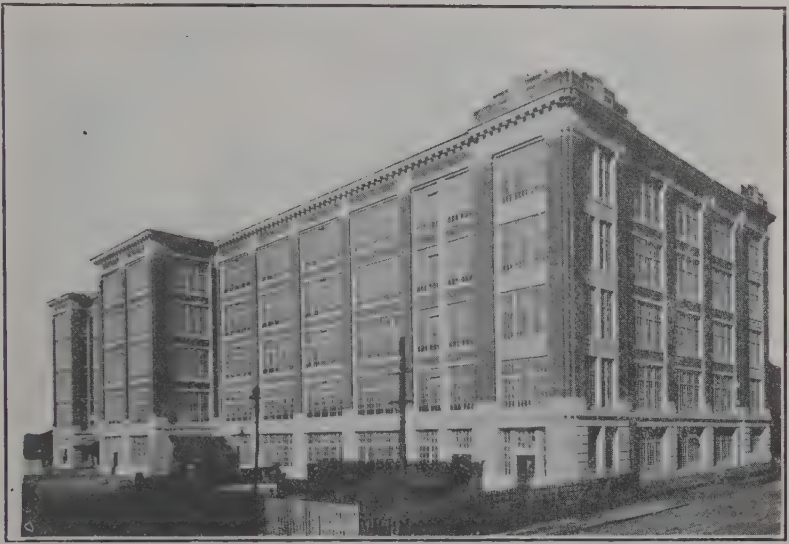

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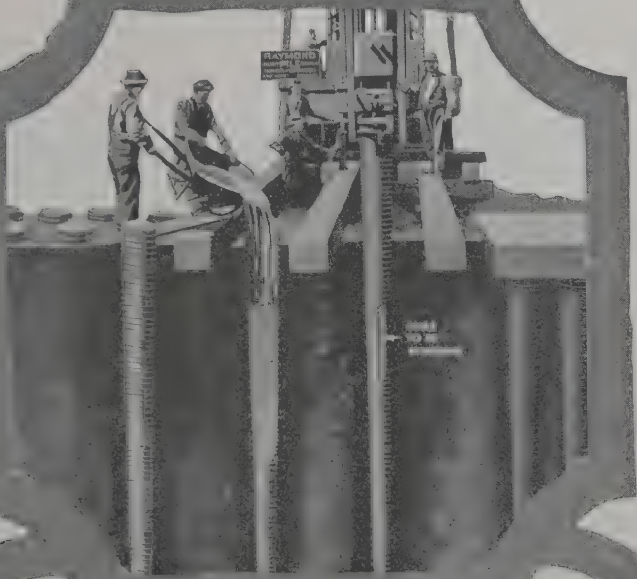

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